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National Technical Information Service

PB-257 951

Hazardous Wastes
A Risk-Benefit Framework
Applied to Cadmium and Asbestos

Stanford Research Inst, Menlo Park, Calif

Prepared for

Environmental Protection Agency, Washington, D C Office of Research and Development

Sep 75

273078

PB 257 951

Final Report
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OFFICE OF RESEARCH AND DEVELOPMENT
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WASHINGTON, D.C. 20460

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CONTRACT 68-01-2915

SRI Project EGU-3561

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.

2.

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE
HAZARDOUS WASTES: A RISK-BENEFIT
FRAMEWORK APPLIED TO CADMIUM AND ASBESTOS

5. REPORT DATE
September 1975

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S) Kendall Moll, Sanford Baum, Erwin Capener,
Francis Dresch, Rose Wright, George Jones,
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8. PERFORMING ORGANIZATION REPORT NO.
EGU-3561

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Stanford Research Institute
333 Ravenswood Avenue
Menlo Park, California 94025

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.
68-01-2915

12. SPONSORING AGENCY NAME AND ADDRESS
Office of Research and Development
U.S. Environmental Protection Agency
Washington, D.C. 20460

13. TYPE OF REPORT AND PERIOD COVERED
Final

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This study develops a decision framework for evaluating hazardous waste standards in terms of social risks and product benefits. The analysis focuses on cadmium and asbestos as examples of land waste disposal problems, but it also estimates waste quantities in air and water. Effects of uncertainties in the individual estimates on overall confidence limits, resultant decision criteria, and research needs are evaluated. The approach encompasses the full chain of variables leading to decision criteria, including (1) wastes escaping into the various media from each step in the hazardous material flow process, including extraction, refining, manufacturing, use, and disposal; (2) cost and effectiveness of alternative waste control measures; (3) their economic, employment, and balance-of-trade effects; (4) environmental dispersion mechanisms; (5) human exposures, dose-damage relationships, and resultant mortalities; (6) risk/benefit relationships; and (7) equity distribution, social acceptance, and other independent criteria. An extensive bibliography is included. This report was submitted in fulfillment of Contract 68-01-2915 by Stanford Research Institute under sponsorship of the U.S. Environmental Protection Agency. Work was completed in September 1975.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT
Release unlimited

19. SECURITY CLASS *(This Report)*
Unclassified

20. SECURITY CLASS *(This page)*

21. NO. OF PAGES
272

22. PRICE

EPA Form 2220-1 (9-73)

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Chapter 1

INTRODUCTION AND CONCLUSIONS

Background

Surveys conducted by EPA indicate that approximately 10 million tons of nonradioactive hazardous wastes are produced in the United States each year. This quantity has been increasing at a 5 to 10 percent annual rate, but federal, state, and local regulations on the control and disposal of these pollutants are either permissive or entirely lacking. If the trend continues, the populace will sooner or later be exposed to undesirably high levels of these pollutants.

Of particular concern is the problem of disposal. Land is being used more frequently as air and water pollution controls become more stringent and hence restrict the alternative media that may receive waste discharges. However, very few standards have yet been established for land disposal of hazardous wastes; those that have been established are based upon incomplete risk and cost estimates. The true costs and risks of land disposal can only be estimated in the larger context of exposures from all sources, but this context is still highly uncertain.

Widespread, low-level risks to health cannot be clearly assessed by deterministic methods of relating pollutant exposure levels to resultant symptoms and illnesses. Probabilistic approaches are needed. Yet, only limited data are available on physiological responses to high dose levels of hazardous materials. Even less data exist on damage to health at low exposure levels. Similarly, simple assessments of the direct costs of control measures are clearly inadequate for assessing the full costs of imposing controls. Indirect costs imposed upon both consumers and producers by changes in the public's "willingness to pay" for products generating the wastes need to be considered. Overall limits to the public's willingness to accept social risk may impose independent constraints on the feasible standards.

For these conditions of information deficiency, a risk-benefit analysis of probable losses and benefits seems most appropriate. Probabilistic estimates of dose levels that may cause injury need to be defined and balanced against comprehensive estimates of the economic costs of reducing or controlling hazardous wastes. Furthermore, a decision-theoretic framework is needed to relate the risk-benefit analysis to the degree of reliability of the input information. Acceptable risk levels may well depend upon the reliability as well as the absolute magnitude of the risk and benefit estimates. Finally, the decision-making process by which society attaches economic values to risks, benefits, and information reliability should be studied so that trade-offs derived by theoretical methods can serve as realistic guides for the disposal of hazardous wastes.

Objectives

The purpose of this research project, as stated in the contract, is to develop "an applied decision-making framework to assess the reliability of environmental standards on hazardous wastes disposal." The scope of work encompasses a six-step effort:

(1) Review the relevant literature to determine the state of the art on economic risk-benefit analysis (see Bibliography).

(2) Develop a decision-making structure to trace the flow of information required to set environmental standards for hazardous waste disposal (see "Approach" in this chapter).

(3) Assess the reliability of decisions about standards in terms of the reliability of the input information (see Chapter 8).

(4) Translate the quantitative information on risks and benefits, wherever possible, into estimates of economic impacts on social welfare (see Chapter 5).

(5) Apply the methods developed to case studies of alternative control programs for asbestos and cadmium waste disposal (examples are given in all the chapters below).

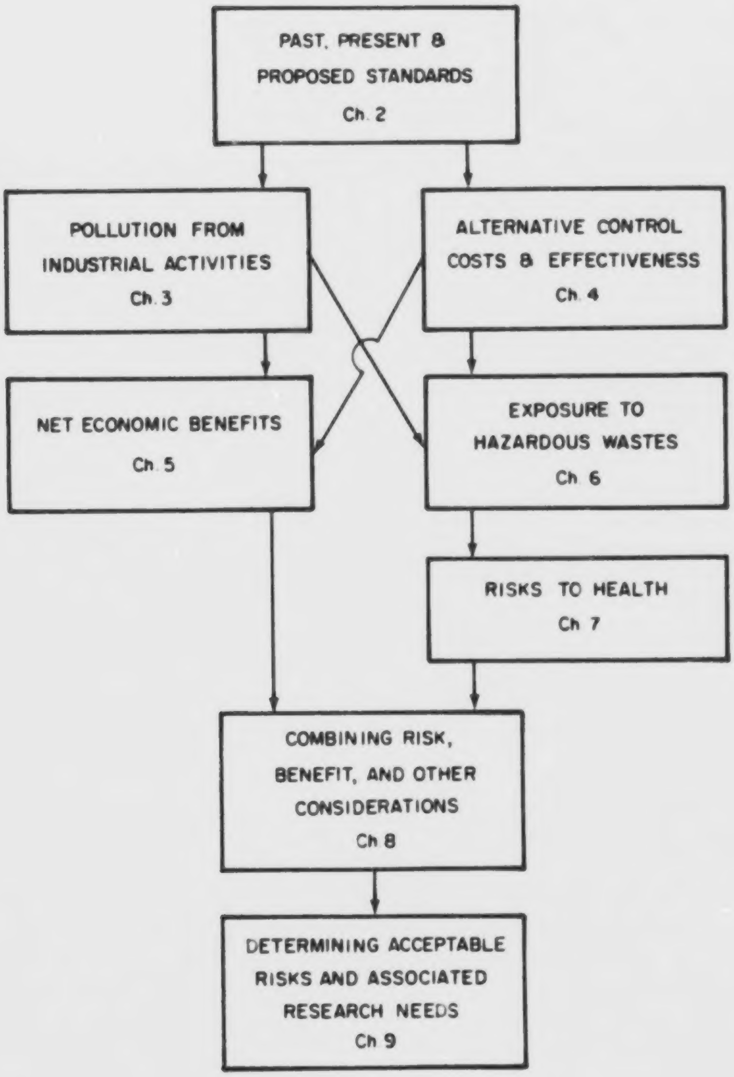
(6) Establish a list of research priorities for compiling information that is found to be crucial to the improvement of decision-making standards (see Chapter 9).

Approach

Answers to the questions posed in the above objectives have been derived here by a multidisciplinary analysis to examine (1) the amounts of emissions and non-health economic benefits from polluting industrial activities, (2) the risks to human health posed by those emissions, (3) the changes in risks and benefits caused by alternative control or substitution measures, (4) the ratios of risks to benefits for the alternatives and the degree of uncertainty in the risk-benefit estimates, and (5) the effects of these ratios and uncertainties, together with other constraints on the problem, on the environmental standards and information needs to be decided by EPA. A logic diagram for these steps is shown in Figure 1-1.

Conclusions

Findings of this study can be logically organized into three general categories: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POLLUTION FROM INDUSTRIAL ACTIVITIES Ch. 3
ALTERNATIVE CONTROL COSTS & EFFECTIVENESS Ch. 4
NET ECONOMIC BENEFITS Ch. 5
EXPOSURE TO HAZARDOUS WASTES Ch. 6
RISKS TO HEALTH Ch. 7
COMBINING RISK, BENEFIT, AND OTHER CONSIDERATIONS Ch. 8
DETERMINING ACCEPTABLE RISKS AND ASSOCIATED RESEARCH NEEDS Ch. 9

FIGURE 1-1 ANALYTICAL STEPS FOR DETERMINING ENVIRONMENTAL STANDARDS AND INFORMATION NEEDS

(1) The methods developed in our work that appear most suitable for a framework to assess environmental risk standards.

(2) Results of applying these methods to example case studies of alternative control programs for asbestos and cadmium waste disposal.

(3) Data from monitoring, research, and other activities that are needed to serve as inputs to the recommended methods.

Conclusions concerning each of these categories from throughout the report are summarized below, together with references to the chapters containing their analytical derivations.

Methods for Determining Acceptable Risks

A "multiple criteria" methodology is suggested here for the quantitative analysis of acceptable risks to life and health from hazardous wastes. In this method, multiple criteria are incorporated in a modified risk-benefit model to generate and display to the decision-maker a feasible operating domain for environmental controls (see Chapter 8). If alternative control programs under consideration are found to be feasible according to the multiple criteria, they can be ranked and chosen by one of many quantitative decision procedures (see Chapter 9).

This methodology goes beyond conventional standard setting and program selection by quantifying and including a wider assortment of the decision factors involved, by formally considering uncertainties in the estimates of each factor, and by orienting the analysis toward presentation for final consideration and choice by the decision-maker rather than toward derivation of an "optimum" programmed solution. The methodology is founded on the axioms that there probably is no unequivocally optimum solution (see Chapter 9) and that, in any event, the responsible decision-maker must make the final choice (see Chapter 8). Consideration of uncertainties, however, is one aspect where formal analysis can assist the decision-maker in handling interrelated random variables (Chapters 4 and 8). Inclusion of as many relevant criteria as possible in the formal methodology also can help the decision-maker reach better decisions; existing standards criteria such as "maximum permissible tolerance," "best feasible technology," and "cost/benefit" all suffer in application from their simplistic assumptions (see Chapter 2).

In outline, the advocated approach starts with an examination of existing standards (Chapter 2) and contamination sources (Chapter 3). These serve to describe the status quo situation against which action alternatives must be measured. The method then examines the costs of alternative control programs and their effectiveness in reducing hazardous waste emissions (Chapter 4). These data are applied in an economic analysis (Chapter 5) and in successive calculations of human exposures (Chapter 6) and resultant health effects (Chapter 7). The resultant risk and benefit estimates for each alternative control are compared with each other and with other decision considerations to determine whether the alternative appears feasible (Chapter 8). If it does, further analyses are carried out to rank its desirability against other alternatives and to assess information needs that may help to resolve relevant issues (Chapter 9).

Perhaps the most demanding aspect of the method is in obtaining an estimate of the risk to health, and its uncertainty range. Flow processes and volumes of the contaminating waste are difficult to obtain; we found it necessary to carry out detailed material balance studies for the wastes we studied (see Chapter 3). Also, such relevant processes as wind dispersion and resuspension, intermedia exchange, environmental buildup, and population mobility each require quantitative submodels (see Chapters 6 and 7). Diverse as these factors are, we found that they could be linked together to obtain overall risk estimates. Risk to health can be adequately measured in terms of excess mortality, the value of which is best expressed by "revealed preference" (Chapter 7).

Benefit estimation requires sophisticated economic techniques to evaluate supply and demand curves in deriving changes of such measures as consumer surplus, profits, employment with and without local multiplier effects, gross national product, and balance of trade (Chapter 5). Our conclusions from these studies were that the most general measure of national economic effects was that relating to gross national product; while the best measure of immediate local effects in the producing areas was one showing employment changes, with appropriate multipliers to reflect impacts on the wider local economy. Unavailability of existing estimates of some benefits unexpectedly forced us to generate new submodels; for example, we found it necessary to derive a rough value of 10 percent of annualized control costs as the estimated add-on cost for government program enforcement and administration (Chapter 4).

In addition to risk and benefit, some of the multiple criteria that can be quantitatively considered in the analysis are (1) maximum acceptable economic costs and government budgets for the program--both short term and long term, (2) maximum acceptable social risks--also both short and long term, (3) minimum reducible risk, (4) valuation of human life, (5) risk aversion, and (6) distribution of risks and benefits among different groups (geographic, economic, ethnic, or generational) in the affected population (see Chapter 8).

Preferences among feasible alternatives can be ranked according to several decision measures, including minimum risk, maximum benefit, maximum benefit/risk ratio, maximum ratio of change in benefit/change in risk, maximum monetary value of benefit less risk, and maximum probability of meeting all constraints. For each measure, various criterion scales can be used, such as probability density, expected value, optimism, pessimism, and regret (see Chapter 9). The decision-maker himself may be expected to use various heuristic procedures in selection that our presentation method has been designed to accommodate. These procedures include pursuit of "satisficing" objectives (satisfying a number of independent criteria instead of optimizing one), preference for "incremental" alternatives (small changes from the status quo), and reliance on information feedback to perfect the original choice (also in Chapter 9).

Results of Studies of Example Hazards

Four example controls--two for cadmium and two for asbestos--were examined by the recommended methodology. Although results indicate that none of the four would be justified, we do not conclude that these controls, much less controls in general, are necessarily undesirable in a broader context. Some of the controls will reduce contaminants besides those analyzed here. Other reasons for this seemingly paradoxical conclusion are explained in the next section of this chapter. Nevertheless, within the scope of our model we found all four controls to be severely deficient from a cost-effectiveness standpoint. The best of the four--the zinc smelter scrubber for control of cadmium emissions--was roughly a factor of 10 below the effectiveness needed to justify its costs in terms of a moderate valuation of human life. The other three controls were 3 or more orders of magnitude (factors of 1,000 or more) below desired efficiencies (see Chapter 8).

The smelter scrubber would look more justifiable if its calculated risk reduction included the effects of other contaminants such as arsenic; but the effects of cadmium alone were minimal except very near the source of airborne contamination. Observed statistical correlations of cadmium air concentrations with urban death rates, a major reason for the current concern over cadmium, appear from our analysis to be at least partly a spurious artifact of the data, rather than a true cause-effect relationship (see Chapter 7). Also, the full effects of cadmium contamination are not reached until after 50 years of cumulative body buildup, but our population mobility model indicates that less than 2 percent of the local population will stay in a highly contaminated community for that length of time (see Chapter 7). Because of these limitations, our model generated a national annual life saving of 5 years each by only 33 people in the smelter areas--a total of 166 person-years per year (Chapter 7). Revealed preference valuations of human life based on risk premiums charged in the labor market are about $300,000, so this saving would total in the order of $1.5 million (see Chapter 8). The saving had to be weighed against a loss of $14 million per year in local industry and support service wages in smelter areas. Nationally, the loss would be about $21 million in GNP. Only abou one-fourth of this loss would be passed on to the consumer if no import restrictions were imposed, because foreign competition would hold down price increases. (This finding differs greatly from the 90 percent pass-on percentage of control costs assumed in another recent study for EPA--see Chapter 5.)

A much more unfavorable risk-benefit ratio could be shown for the other cadmium control--scrubbers on municipal incinerators. Because municipal incinerators account for only a small part of incinerated waste, the number of lives saved are much lower: one-tenth person-year per year. But the national costs to install scrubbers on the numerous municipal incinerators would be even higher: $28 million per year.

Finally, the two asbestos alternative controls--filters on asbestos manufacturing exhausts and substitute materials to replace asbestos in automobile brakes--showed negligible risk reductions. The original air concentrations of asbestos from these sources, even around the production facilities or near busy streets, were too low to be dangerous (Chapter 7). (Handling of asbestos in the working place or elsewhere was not considered.) Yet the costs, which would be primarily passed on to consumers, were substantial because of the widely dispersed sources. Costs for controlling asbestos production facilities would be only about $3 million per year, but replacing asbestos brakes with a hypothetical replacement material could cost $65 million per year (see Chapter 5).

Uncertainties were large for all of the alternatives, but not large enough to change the conclusions about any of them (Chapter 8). What conceivably could change the conclusions are unknown and exogenous factors, such as undiscovered hazards or substitute materials, that were not considered in the model.

Monitoring and Research Data Needs

Many data elements were either assumed subjectively or adopted on the basis of very tentative evidence for this study, which is intended primarily to demonstrate a methodology rather than to provide authoritative conclusions about technical issues. These data elements can be greatly improved by successive iterations. In addition to broadening the model to include the effects of controls on additional hazardous wastes, as mentioned earlier, several types of feedback and data refinements are needed. As EPA and other agencies have discovered, reviews by technical experts acting in adversary capacities will quickly elucidate the range of informed opinion on any subject and will correct initial errors in analysis. Iterations of the analysis will help to resolve conflicting uncertainties, assumptions, and constraints in the formulation. Eventually they will lead to discovery and inclusion of originally unknown factors such as long-term and ecological effects, which have been ignored here.

Any of these prospects could conceivably modify our analysis enough to change our original conclusions; we expect that a pattern of successive refinement is characteristic of any dynamic standards development process. Beyond this evolutionary process of technical knowledge development, however, more revolutionary improvements can be realized by considering information for environmental standards as elements in a knowledge system that must parallel the physical processes involved in contamination (see

Chapter 2). Data in much of the existing literature are not complete enough to be useful for the larger analytical purposes of such a system.

For example, emissions may be given in pounds per minute without indicating how many minutes per day or days per year the emissions continue, thus precluding any authoritative estimate of the most meaningful parameter: annual rates. Or, health effects experiments may be reported in terms of median lethal dose for rats, without (1) providing any clue of a reasonable transfer function to obtain the relevant variable of human deaths, or (2) supplying data for other dose levels that might permit estimation of a complete dose-damage function. Without a complete dose-damage function, there is no way to estimate the value of a threshold dose. Without a reasonable threshold dose estimate, there is no logical basis for promulgating maximum permissible dose standards.

Standard setting as well as information gathering can gain from a systematic approach. All of the standards in the system, whether of production rates, usage, emissions, media concentrations, personnel exposures, or actual ingestion should be related to each other in a systematic way that reflects the flow processes involved. This kind of standards integration does not presently exist for either cadmium or asbestos (see Chapter 2).

If this kind of flow process and its uncertainties can be defined quantitatively, then it will be possible to determine the ultimate value (but not necessarily the practical value) of research on any component or stage of the process. This can be done by calculating the "expected value of perfect information" and comparing it to the value of other research efforts or to the expected value of implementing a control program. In this way, the relative potential payoff of research efforts can be estimated as an aid to research planning and to deciding whether program implementation or further study would be most desirable (see Chapter 9).

Finally, we have examined a large number of source materials in the course of this study (see Bibliography) and have made some conclusions about current technical data needs. We found that hazardous waste research studies generally give inadequate attention to the analysis of uncertainty, and to generalizing their results for policy applications. Concerning cadmium, better data are particularly needed on the industrial processes involved and their wastages, on dispersion patterns into food and water, and on long-term mechanisms of biological uptake. Asbestos research is especially needed to find more uniform standards, better concepts of contamination mechanisms, and more accurate estimates of cumulative dose histories (see Chapter 9).

Chapter 2

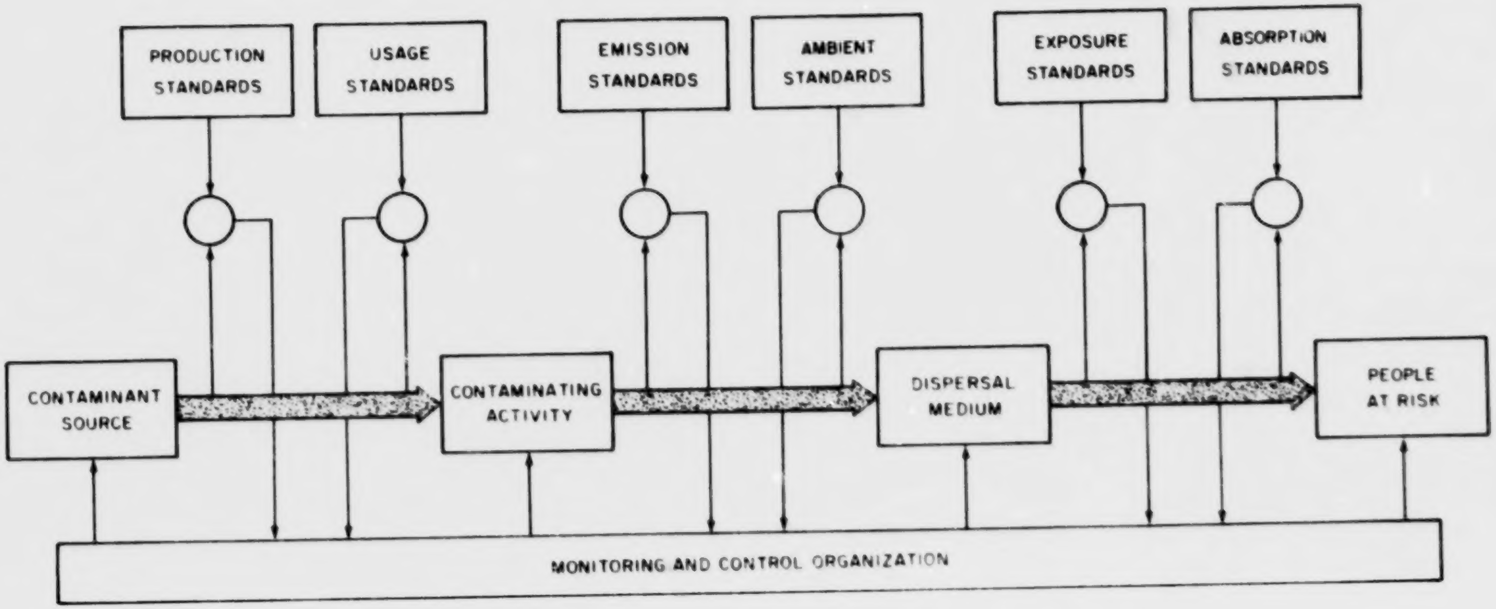
PAST, PRESENT, AND PROPOSED STANDARDS

To be complete, a study of methods for determining acceptable risks from hazardous wastes should start with existing premises and precedents. Accordingly, in this chapter we review the functions of standards and trace the development of these standards as they have evolved over time. Finally, a methodology is proposed for setting standards, followed by a description of how the methodology will be applied in subsequent chapters of this report.

Standards from a Systems Viewpoint

When the process of hazardous waste production and pollution is viewed as a man-made system, its contaminant levels can be considered as parameters to be controlled. Standards can then be seen as performance goals for controlling the contaminant parameters. Each standard represents a value that can be compared to a physical measure. These system concepts are illustrated in Figure 2-1, which shows several types of physical measures that can be balanced against a comparison standard to obtain a control signal. It also shows that the control signal serves as an input to influence either the contaminating activity itself or some other component of the larger system.

For precision, the best comparison signal is one furthest "downstream" (for example, absorption levels in Figure 2-1), since that gives the most accurate measure of the overall contamination problem. However, the downstream feedback signal also tends to be the slowest and sometimes the most erratic, so that error signals from further upstream in the process also can be helpful.


PRODUCTION STANDARDS
USAGE STANDARDS
EMISSION STANDARDS
AMBIENT STANDARDS
EXPOSURE STANDARDS
ABSORPTION STANDARDS
CONTAMINANT SOURCE
CONTAMINATING ACTIVITY
DISPERSAL MEDIUM
PEOPLE AT RISK
MONITORING AND CONTROL ORGANIZATION

SOURCE: SRI

FIGURE 2-1. STANDARDS, MONITORING, CONTROLS, AND CONTAMINANT FLOW IN THE HAZARDOUS WASTE SYSTEM

The complexity of the comparison standard represents another dimension of control. Standards can vary from crude rules of thumb to highly sophisticated, dynamically changing values. In roughly increasing order of complexity, environmental standards can be categorized according to the following types of criteria:

Zero Tolerance--An absolute ban on any observable amount of contamination. While simple and easily interpreted, this type of standard is often impractical to enforce if monitoring measurements are sensitive enough to detect low levels. Otherwise, zero tolerance will usually preclude any significant use of the hazardous material.[1]

Permissible Limits Established on the Basis of Health Effects--If health effects are used to determine tolerance, they can be categorized according to the type of evidence on which they are based.[2]

- Acute effects--quickly noticeable clinical evidence in man.
- Chronic effects--clinical evidence that becomes noticeable only after a cumulative exposure or after a lengthy delay period.
- Indirect evidence--epidemiological evidence from statistical experience with a meaningfully large population.
- Laboratory evidence--animal (in vivo) and cell culture (in vitro) effects.

In all of these cases, the standards are usually established relative to some "threshold exposure that represents the lowest noticeable level at which injuries occur. The threshold levels (where they can be observed) are higher for acute than for chronic effects, and higher for chronic than for indirect effects; so standards set on chronic and indirect effects usually incorporate safety factors to allow for these differences. But great variations can exist; even for the same effect, the standard can vary by a factor of 10 or more, depending upon whether or not homeostatic adjustments that compensate for effects are considered permissible.

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[1] "Permissible Levels of Occupational Exposure to Airborne Toxic Substances," World Health Organization, Technical Report Series No. 415, Sixth Report of the Joint ILO/WHO Committee on Occupational Health (1969).

[2] T. F. Hatch, "Criteria for Hazardous Exposure Limits," Arch. Environ. Health, Vol. 27, pp. 231-5 (October 1973).

If there is no lower dosage limit to injuries (i.e., if no threshold is observable), then a standard based only on health effects is not very logical, since no one can say at what level (except zero) the health effects become insignificant. Even with a threshold a health standard, like a zero tolerance standard, gives no consideration to the economic or other difficulties involved in achieving the specified contamination level.

Process Specifications--Procedural or process conditions imposed on contamination controls can form a standard based on opposite considerations; i.e., one dictated by the economic and other difficulties involved without explicit consideration of the health hazards involved. This type is equivalent to a "best technology" standard (sometimes qualified by words such as "practicable" or "feasible") in which technical considerations dominate. As a temporary start-up standard or where the actual health hazards are very uncertain or indeterminate, this criterion can be a logical one; but where reasonable health effects data are available, some means of balancing health effects against control technology seems a much more rational approach.

Risk-Benefit--A standard based on the ratio of the health and safety risks to the economic and other non-health benefits provided by the contaminating activity. This ratio does balance the health and economic effects of any control alternative, and accordingly it has recently been viewed as a promising method of standard setting. It can be established either in common money terms, or in two dimensions (e.g., health and economic). But either way, it is expressed in quantitative terms representing some kind of tradeoff between health effects and economic effects of the standard. It does not reflect possible inequities in who gets which effects, nor does it consider other potential influences such as public acceptability.

Multiple Criteria--A combination of criteria to approximate the complex balance among health, economic, political, and demographic considerations that actually exist in real-life standard-setting situations. All of these considerations are needed to achieve a durable and acceptable standard. To date, there have been few, if any, formal attempts to design and implement a multiple criteria standard, but the present report outlines a methodology that can be applied to such an effort. Our approach to the problem is to include conventional risk-benefit criteria modified by other economic factors such as effects on consumer and producer surpluses, substitution possibilities, joint effects of controls and enforcement costs. Other criteria to be introduced include maximum socially acceptable risk levels, distinctions in risk-benefit trade-offs between producing and consuming areas, and effects of uncertainties in both costs and benefits on the overall decision problem.

Whatever standards are developed for a contamination system, feedback from the comparisons of standards with measured conditions must be implemented by means of controls upon one or more of the components of the system. Figure 2-1 shows schematically how monitored signals might be used to control the contaminant flow at any point in the system. However, the exact mechanism by which these controls would operate is not described. In the case of environmental standards, the controls can operate through three compliance mechanisms: (1) voluntary cooperation, (2) regulatory controls, or (3) economic forces. Analyses of the effectiveness of these various mechanisms become quite involved. This compliance component of the waste contamination system is outside the scope of the present study and will not be addressed here.

The Development of Present Standards

Safety standards in the use of hazardous materials follow a typical pattern of development. Initially, new materials and new uses of old materials tend to be discovered and exploited without much regard for their safety or health hazards. Examples of this phase are the early uses of lead (which lasted hundreds of years before its health dangers were recognized) and of radium (which lasted only a few decades before strict restrictions were imposed). Eventually, even primitive cultures usually learn by trial and error to deal with the hazards of a given material. Society develops what are often quite rigid control measures in the form of regulations, folk wisdom, or taboos to protect itself against the most obvious hazards of contaminants.

With the rise of the scientific spirit, safety standards have become somewhat more quantitative and cause-effect related. Standards are set on the basis of explicit, objective criteria for clearly recognized causes. These tendencies became institutionalized by the rise of public health organizations about a hundred years ago and have led to a continuous rapid drop in the incidence of such hazards as lead and zinc poisoning. However, many of the initial standards were merely advisory or permissive, or if mandatory they were often not fully enforced.

In a third phase, authorities have recently tended to set stricter standards as they have become more aware of the need for caution due to chronic and indirect effects. Generally, additional adverse effects have been discovered by intensive epidemiological studies, both clinical and experimental, such as those carried out on the hazards of tobacco. These studies and the resultant better knowledge of biological effects were major causes of popular pressures in the United States for stricter environmental and occupational health standards, leading to such recent statutes as the Solid Waste Disposal Act of 1965, Resource Recovery Act of 1970, Clean Air Act of 1970, Water Pollution Control Act of 1972, National Environmental Policy Act of 1969, and Occupational Safety and Health Act of 1970.

Example: Cadmium--Cadmium represents an interesting example of the standards development process because its entire industrial experience has occurred during relatively recent history. Cadmium was only discovered in 1817 and the first recorded incident of cadmium poisoning occurred in 1858.[3] Its high toxicity provided extensive medical documentation of the acute effects--encountered from air, water, and food ingestion--in industrial and other exposure cases and led to the banning of cadmium in certain applications, such as in cooking and eating utensils. However, its role in chronic poisoning was not widely recognized until an epidemic of itai-itai (ouch-ouch) disease, with kidney and bone symptoms of proteinurea, osteomalacia, and osteoporosis, was documented in Japan. The cause was eventually traced to mine dumping beginning about 1924 in a river being used as a supply for drinking water and rice irrigation. Symptoms among local inhabitants began to be noticed about 1935, and almost 100 deaths attributable to the disease had occurred by 1965. Yet its endemic nature was not recognized until 1955, and at least two false leads (nutritional deficiencies and zinc poisoning) were followed until cadmium was identified as the probable poison in 1961. Legal responsibility for the contamination was not determined until 1971. Further investigations near other zinc mines in Japan found at least one additional locality where deaths and disabilities from itai-itai disease had previously been unrecognized (Fulkerson, Chapter VI-C).

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[3] W. Fulkerson et al., "Cadmium--the Dissipated Element," ORNL NSF-EP-21, supported by the National Science Foundation RANN Program, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

On the basis of an estimated minimum ingestion of 600 micrograms of cadmium per day for itai-itai disease sufferers (ten times normal), the Japanese Ministry of Health established a maximum acceptable ingestion level of 300 micrograms per day from food and drink. More recently, the World Health Organization[4] has recommended a "provisional tolerable weekly intake" of 400 to 500 micrograms, about 60 micrograms per day. Inhalation through the air is almost negligible compared to food and water ingestion, except for heavy smokers and workers in certain industrial installations.

It is interesting to note that these standards apply to the very last of the types of measurable system outputs that are shown in Figure 2-1 (absorption). To regulate contamination efficiently, additional standards are needed for other more directly controlled outputs that occur upstream in the flow process, such as levels of exposure, concentrations, emissions, usage, or production. For example, absorption might best be controlled by limiting total amounts eaten in food, the dominant contributor to cadmium ingestion, or by controlling the maximum concentrations allowed in food substances. Food at present has no standard either for maximum cadmium exposures or for maximum cadmium concentrations.

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[4] "Evaluation of Certain Food Additives and the Contaminants Mercury, Lead, and Cadmium," Sixteenth Report of The Joint FAO/WHO Expert Committee on Food Additives, Geneva, 4-12 April 1972, World Health Organization Technical Report Series, No. 505, FAO Nutrition Meetings Report Series, No. 51 (1972).

Water and air also have no media standards that apply to total exposure by individuals. However, both have concentration standards. Drinking water has a tentative World Health Organization[5] cadmium concentration limit of 0.005 mg/l and a U.S. limit[6] of 0.01 mg/l. Air is limited under U.S. occupational health regulations to concentrations of 0.1 $\mu g/m^3$ cadmium fume (0.2 $\mu g/m^3$ cadmium dust) for an 8-hour work shift.[7]

Emission standards have been established for water but not yet for air. Proposed cadmium effluent limits for streams or lakes of hardness less than 100 mg/l $CaCO_3$ are a maximum concentration of 70 $\mu g/l$, a maximum weight of 0.035 kg/day times the receiving water design flow in m^3/sec, and a maximum cadmium discharge per facility of 9.8 kg/day where more than one facility is discharging. For freshwater bodies of water hardness greater than 100 mg/l $CaCO_3$, and for estuary and coastal waters, the limits progressively rise.[8] For ocean dumping, waste concentration limits have been set at not more than one order of magnitude higher than the local cadmium content of actual seawater.[9]

No standards have been set to control the usage of cadmium, except that the FDA bans cadmium-containing materials for use in food preparation and food packaging (Fulkerson, 1973, p. 351).

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[5] S. Hernberg, "Health Hazards of Persistent Substances in Water," WHO Chronicle, Vol. 27, No. 5, World Health Organization, Geneva, pp. 192-3 (May 1973).

[6] "Interim Primary Drinking Water Standards," Environmental Protection Agency, Federal Register, Vol. 40, No. 51, Part II, pp. 11990-98 (14 March 1975).

[7] "Occupational Safety and Health Standards," Occupational Safety and Health Administration, Federal Register, Vol. 37, No. 202, Part II, pp. 22102-22356 (18 October 1972).

[8] Toxic Materials News (15 January 1975).

[9] "Ocean Dumping," U.S. Environmental Protection Agency, Federal Register, Vol. 38, No. 94, pp. 12872-7 (16 May 1973).

From the control systems standpoint of Figure 2-1, then, present cadmium standards are seen to be either of the zero-tolerance (food-touching materials) or permissible-limit (e.g., air and drinking water) categories. Standards based on cost-benefit or multiple-criteria approaches are notable by their absence. The relationships between standards, monitoring, and control do not seem to be very systematic or comprehensive. Several potential monitoring points (e.g., cadmium production) have no present standards, and the means of control for other standards (e.g., food) are not at all clear.

Example: Asbestos--Asbestos presents a history of standards development similar to that of cadmium, even though it has been used as a novelty in lamp wicks and even tablecloths since antiquity.[10] The first recorded case of a disease related to asbestos fibers was in 1907, but the symptoms of asbestosis were not determined until 1927, and the hazards of lung cancer from inhalation of asbestos were not established until 1947. The first definitive epidemiological study of the effect of asbestos was only undertaken in the early 1960s by Selikoff and his colleagues.[11]

Development of standards for asbestos have been further delayed by difficulties in counting submicron size fibers. One nanogram may represent a million fibers. In sprayable insulation formulations, asbestos fibers can only be reliably counted by electron microscope techniques costing $300 per sample.[12] Air sampling by this technique costs even more.

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[10] J. S. Horvitz, "Asbestos and Its Environmental Impact," Environ. Affairs, Vol. 3, No. 1, pp. 145-65 (1974).

[11] A. K. Ahmed, D. F. MacLeod, and J. Carmody, "Control for Asbestos," Environment, Vol. 14, No. 10, pp. 16-22 (December 1972).

[12] "Background Information on the Development of National Emission Standards for Hazardous Air Pollutants: Asbestos, Beryllium, and Mercury," APTD-1503, Office of Air and Water Programs, U.S. Environmental Protection Agency, p. 34 (March 1973).

In 1946, the first U.S. standard established a concentration threshold limit value equivalent to 30 visible particles per milliliter in the air of working spaces. This occupational standard was reduced to 12 fibers of greater than 5 micron length per milliliter in 1968, to 5 in 1971, and to 2 effective in 1976.[11] However, the visual methods currently used to count asbestos concentrations account for less than 5 percent of total fibers, and no one knows whether the visually identifiable fibers are any more significant to health effects than the smaller fibers (Ref. 12, p. 24).

Because of these monitoring difficulties, many responsible agencies have begun by regulating inputs to the contaminating activity (i.e., production and usage of the contaminant) rather than outputs (emissions, concentrations, and the like). Several local and state jurisdictions, such as New York, Boston, Philadelphia, and the State of Illinois, have issued regulations restricting and controlling the usage of asbestos in specific construction operations. EPA has continued this approach in its regulations over manufacturing and extraction point sources, as in the Reserve Mining case. Where appropriate in the case of air pollution, it has applied a nonquantitative "no visible emissions" requirement.

Generally, then, we can characterize the emphasis in asbestos controls to be more input-oriented than output-oriented, and more concerned with qualitative than with quantitative criteria. Many potential observation points in the "hazardous waste system" shown in Figure 2-1 are not monitored, and few of those that are monitored seem designed to give very precise, comprehensive, or reliable assessments of the true hazards from asbestos. As is the case with cadmium, no current asbestos controls even attempt to regulate on the basis of cost-benefit or multiple-criteria models.

A Proposed Methodology for Future Standards

The foregoing examples point directly to ways by which future standard-setting can be improved. Consideration of the flow of hazardous wastes as a man-made system can make standards:

(1) More systematic--Individual controls and monitoring points need to be considered as parts of the entire system shown in Figure 2-1 rather than as entities unto themselves. If the balance between controls is not considered, some will dominate the material flow and form artificial bottlenecks.

(2) More comprehensive--The systems perspective shows how additional controls can be used to improve the overall response of the system, and how neglected control points might be highlighted by careful analysis. At the same time, interactive systems effects will permit overall control to be exerted without having monitors or controls at every point.

(3) More reliable--Monitoring information can also be used to verify information from other components in the system, and controls over one component can reinforce the effects of controls over another.

(4) More precise--Coordinated use of controls can provide a precision impossible with individual controls. This precision can be designed by making use of the feedback relationships among the system components and controls.

(5) More adaptive--The use of more sophisticated control standards, such as multiple criteria models, will permit the system to (1) reach a better balance between social objectives, (2) to remain more consistently in a self-regulated state without outside policy interference, and (3) to

address more effectively many of the types of policy criticisms that have been directed at present and past environmental standards.

The standard-setting methodology by which hazardous waste systems can be better controlled must be based on multiple criteria, which are described in the subsequent parts of this report. Once standards are set in a systematic manner, monitoring and control procedures can be designed for effective and equitable control over the entire system.

Chapter 3

POLLUTION FROM INDUSTRIAL ACTIVITIES

General Methodology

Background

A great deal of literature has been generated over the years describing production, use, and disposal of hazardous materials. However, the bulk of this literature concerns micro-scale experiments and specialized data-gathering efforts. In terms of the larger risk and benefit objectives of this project, not enough past efforts deal with the macro-level problems associated with disposition of hazardous wastes. For example, very few previous studies have attempted to quantify the mass balance characteristics of production, use, and disposal processes, and few have examined the major large-scale mechanisms of waste dispersion over the country.

Objectives and Scope

The objectives of this chapter are to describe and quantitatively assess the emissions of designated hazardous materials into the environment, and to associate these emissions with specific economic activities. The magnitudes of these emissions should also be related to the natural occurrence of hazardous materials in the environment.

The coverage should include emissions of hazardous by-products from the production or use of other materials, as well as directly from materials that are themselves produced and used in the economy. The major focus of interest is the United States and individual regions, states, and localities within the United States, but other countries and the world as a whole will be considered when needed.

Method of Analysis

The approach used in this portion of the analysis consists of the following steps:

(1) Describe the various uses of the hazardous material in the U.S. economy.

(2) Outline the quantities and facilities associated with the flow of the material through its various processing stages, such as extraction and refining, production, use, and eventual disposal.

(3) Assess the nature and amounts of emissions to the environment at each stage.

(4) Describe other controllable sources of human exposure to the hazardous material, such as its occurrence as a by-product, impurity, or waste in the production and use of other materials.

(5) Outline the quantities of economic flow or natural appearance of these indirect sources of the material.

(6) Assess the nature and amounts of emissions to the environment from these secondary sources.

(7) Sum the total of all forms of emissions to the environment by medium (air, land, water) and by location. Variances in the emission estimates are not considered in this chapter, since the model's mass-balance feature helps to limit any systematic errors.

Illustrative Application: Cadmium

Cadmium enters our environment directly as a mineral resource used in industrial activities; indirectly as a by-product of agricultural, construction, energy production, and transportation activities; and naturally as an element in food, water, and the earth's crust. EPA contractors have traced many of its emissions into the atmosphere, but they have been much less successful in finding sources of waste cadmium in surface waters. Likewise, data on the amount of cadmium discarded to landfill are nonexistent, although strong inferences can be made on the basis of known dispositions of most cadmium-containing products.

We have used a selected portion of the available data and derived reasonable estimates where data were not available to calculate a material balance of the man-made flow of cadmium into and out of our environment. We have deferred consideration of its natural concentrations until Chapter 6.

Pollution from the Extraction and Refining of Zinc, Lead and Copper Ores

Cadmium is purified as a by-product in the extraction of zinc, lead, and copper from their ores. Consequently, the amount of cadmium produced is dependent upon the production of these other metals. The Bureau of Mines[13] has developed regression equations which relate cadmium production to both cadmium prices and zinc production. High cadmium prices encourage the importation of zinc ores and flue dusts.

The major flow paths from industrial production and use of cadmium are given in Figure 3-1. For the most part, the indicated flow reflects waste quantities generated in 1968, when U.S. consumption was slightly higher than at present. All of the major flows have been indicated so that the material balance can be realistically modeled. However, the scattered evidence available from EPA[14] and other sources on industrial

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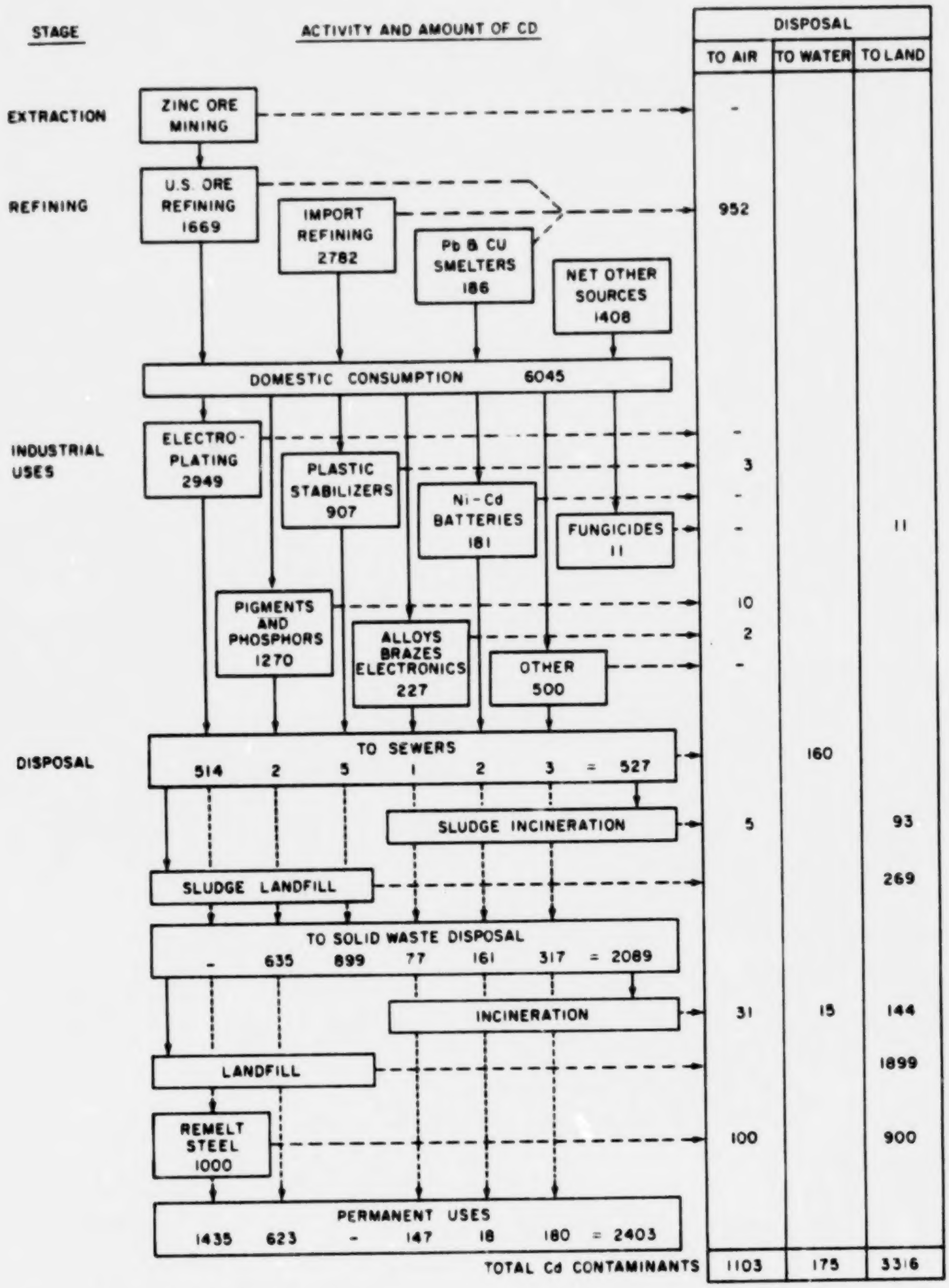
[13] A. Petrick, et al., "The Economics of By-Product Metals," "II. Lead, Zinc, Uranium, Rare Earth, Iron, Aluminum, Titanium, and Lithium Systems," Bureau of Mines Information Circular 8570 (1973).

[14] R. S. Ottinger, et al., "Recommended Methods of Reduction, Neutralization, Recovery, or Disposal of Hazardous Wastes," 16 volumes prepared for Environmental Protection Agency by TRW Systems Group, PB224579, Set/As, Vol. XIV (February 1973).


STAGE
ACTIVITY AND AMOUNT OF CD
DISPOSAL
TO AIR
TO WATER
TO LAND
EXTRACTION
ZINC ORE MINING
-
REFINING
U.S. ORE REFINING 1669
IMPORT REFINING 2782
Pb & CU SMELTERS 186
NET OTHER SOURCES 1408
952
DOMESTIC CONSUMPTION 6045
INDUSTRIAL USES
ELECTRO-PLATING 2949
-
PLASTIC STABILIZERS 907
3
Ni-Cd BATTERIES 181
-
FUNGICIDES 11
-
11
PIGMENTS AND PHOSPHORS 1270
10
ALLOYS BRAZES ELECTRONICS 227
2
OTHER 500
-
DISPOSAL
TO SEWERS
514 2 5 1 2 3 = 527
160
SLUDGE INCINERATION
5
93
SLUDGE LANDFILL
269
TO SOLID WASTE DISPOSAL
- 635 899 77 161 317 = 2089
INCINERATION
31
15
144
LANDFILL
1899
REMELT STEEL 1000
100
900
PERMANENT USES
1435 623 - 147 18 180 = 2403
TOTAL Cd CONTAMINANTS
1103
175
3316

Source: Derived by SRI from multiple sources.

FIGURE 3-1 CADMIUM PRODUCTION, USE, AND DISPOSAL QUANTITIES IN THE U.S. (Metric Tons per Year)

flows to land and water limited the precision of our estimates of those quantities. The data on air emissions are from W. E. Davis & Associates.[16]

Pollution from Cadmium Use

The three major uses of cadmium are (1) electroplating, which accounts for 49 percent of the total; (2) pigments and phosphors, 21 percent; and (3) plastic stabilizers, 15 percent. In the electroplating market, the largest use (10 percent of all uses) is for motor vehicle parts such as nuts, bolts, screws, springs, fasteners, washers, rivets, and carburetor and alternator parts. About 6 percent of all uses go for plating small aircraft parts. The remaining electroplating usages were for radio and television chassis, electrical appliance parts, marine equipment, hardware, and industrial machinery. (A recent SRI study* shows the percentages declining for vehicles and rising for aircraft.)

No cadmium air emissions are reported for the electroplating industry by Davis.[16] Similarly, Fulkerson[3] assigns no discharge to sewage from electroplating. However, numerous other investigators have found large quantities of cadmium discharges from electroplating. TRW[14] estimates that this industry is the largest cadmium polluter of our sewers, with an estimated loading of 514 metric tons per year.

Current statistical data for other industrial uses are also uncertain, although we have estimated disposals to achieve the balance shown in Figure 3-1. Air emissions for all industrial uses total only 16 metric tons.[16] Because of the paucity of water and land pollution data for cadmium (e.g., the only admitted polluter is the nickel-cadmium battery industry,[14]), we have assumed that 50 percent of the pigments and phosphors and 100 percent of the plastics containing cadmium stabilizers end up in waste dumps. The unaccounted cadmium used in pigments (623 metric tons) is assumed to remain in permanent use as paint. The assumed solid waste disposals of the remaining uses are as follows: one-third of the cadmium in alloys, silver braze, and others; two-thirds of the fungicides, nuclear energy, rubber curatives, photography, and unaccounted uses; and 90 percent of the nickel-cadmium battery output. The rest goes to permanent uses.

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[16] "National Inventory of Sources and Emissions: Cadmium, Nickel, and Asbestos--1968," (Cadmium, Section I), PB 192250, prepared by W. E. Davis & Associates, Leawood, Kansas for National Air Pollution Control Administration (February 1970).

*Personal communication, Charles Turk, SRI.

Pollution from Cadmium Disposal

According to Baum and Parker,[16] disposal of all kinds of solid wastes amounted to 354 million metric tons in 1972. We estimate that roughly 9 percent or 32 million metric tons are incinerated--slightly more than twice the 15 million metric tons found incinerated in municipal incinerators by an EPA survey.[17] A proportionate 9 percent of the 2,089 metric tons of cadmium probably go through the incineration process. With emission factors of 0.4 gram per metric tons for controlled and 1.5 grams per metric ton for uncontrolled incineration as given by EPA,[18] this process allows 31 metric tons to escape to the air. The remainder is buried with the ash as landfill, which runs off with water used to cool the ash. The cadmium not incinerated is also assumed to be buried as landfill.

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[16] B. Baum and C. H. Parker, "Solid Waste Disposal," Vol. I, "Incineration and Landfall," Ann Arbor Science Publishers (1973).

[17] W. C. Achinger and L. E. Daniels, "An Evaluation of Seven Incinerators," pp. 32-64 in Proceedings of 1970 National Incinerator Conference, Cincinnati, Ohio, 17-20 May 1970, published by The Amer. Soc. Mech. Engrs., New York, N.Y.

[18] D. Anderson, "Emission Factors for Trace Substances," PB-230894, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards (December 1973).

Recovery of scrap steel accounts for pre-control air emissions of 1,000 metric tons of cadmium per year according to Davis.[15] If we accept the argument that these emissions are well controlled, as implied by Fulkerson,[3] then electrostatic precipitation with a 90-percent effectiveness factor results in 100 metric tons to the air and landfill disposal of the remaining 900 metric tons.

Of the 11 metric tons of cadmium used in fungicides, only 0.2 are released as air pollutants; the remainder are applied principally to golf courses. Much of this probably ends up in ground waters, but in any event, the magnitudes involved are relatively small so we show this usage disposed to land.

Our final accounting for pollution from cadmium disposal is a material balance around the sewage plant. The water wastes from the electroplating, pigment, and battery industries are from TRW.[14] We estimate that 0.5 percent of the amount of cadmium used in the plastic stabilizer alloy, and "other" industries (nuclear energy, rubber curing, photography, and unaccounted) is wasted to the sewer. Therefore, cadmium waste pollution by way of sewage amounts to 527 metric tons per year.

Disposal of these sewage wastes was calculated as follows: According to EPA,[19] an estimated 3.8 million liters of sewage is generated daily by 10,000 people; so for a population of 200 million, some 7.6×10^{10} liters per day are sent to sewage plants. The sewage plants remove most of the cadmium with the sewage sludge. If we take EPA's estimates of sludge generated by primary and secondary treatment plants, and assume that each type treats half of the nation's sewage, the total sludge generated will be in the range of 14,000 metric tons per day, or 5 million metric tons per year. If Page's[20] mean cadmium content of 75 ppm in the sludge is assumed, then the cadmium removed in the sludge will be 367 metric tons per year--about 70 percent of the total cadmium input.

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[19] "Sewage Sludge Incineration," U.S. Environmental Protection Agency, Task Force for the Office of Research and Monitoring, PB-211323 (August 1972).

EPA estimates that 3,600 metric tons per day (1.3 million metric tons per year) of sludge are incinerated. From this, we calculate that incinerated sludge will contain 98 metric tons per year of cadmium. Since the EPA[18] cadmium emission factor of 4 ppm for sludge incineration implies that 5 metric tons per year will be emitted to the air, the remaining 93 tons will be dumped as landfill. The cadmium in sludge that goes directly to landfill without incineration amounts to 269 metric tons.

The portion of cadmium not collected in sludge amounts to 160 metric tons. Thus, sewage effluent discharged to surface waters contains an average 0.006 ppm of cadmium. This estimate compares reasonably with that of Page,[20] who gives a median effluent concentration of 0.005 ppm from a survey of 57 Michigan sewage plants.

Cadmium Contamination from Other Sources

Cadmium also pollutes the environment indirectly as a result of man's agricultural, construction, energy production, and transportation activities. These sources are summarized in the following paragraphs together with an overall accounting of cadmium pollution in the three media, and are outlined in Figure 3-2.

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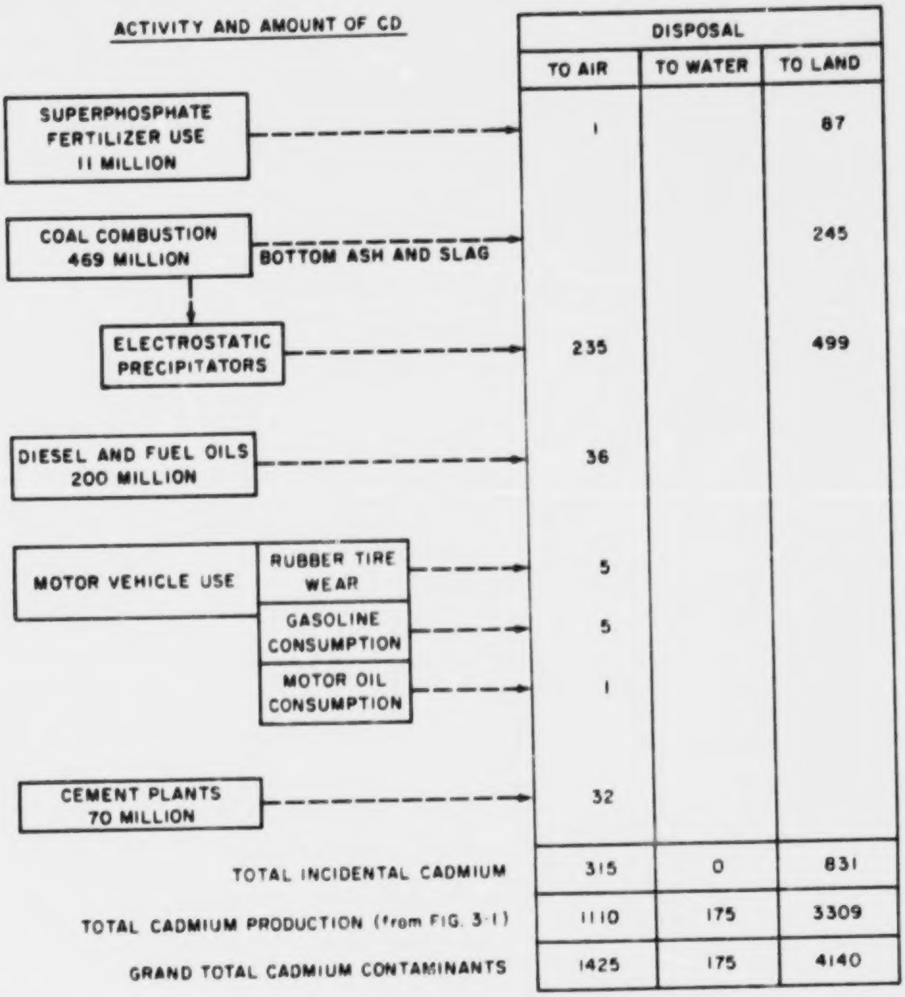
[20] A. L. Page, "Fate and Effects of Trace Elements in Sewage Sludge When Applied to Agricultural Lands--A Literature Review Study," PB 231171, EPA 670/2-74-005, Univ. of Calif., Riverside, Calif. (January 1974).


ACTIVITY AND AMOUNT OF CD
DISPOSAL
TO AIR
TO WATER
TO LAND
SUPERPHOSPHATE FERTILIZER USE 11 MILLION
1
87
COAL COMBUSTION 469 MILLION
BOTTOM ASH AND SLAG
245
ELECTROSTATIC PRECIPITATORS
235
499
DIESEL AND FUEL OILS 200 MILLION
36
MOTOR VEHICLE USE
RUBBER TIRE WEAR
5
GASOLINE CONSUMPTION
5
MOTOR OIL CONSUMPTION
1
CEMENT PLANTS 70 MILLION
32
TOTAL INCIDENTAL CADMIUM
315
0
831
TOTAL CADMIUM PRODUCTION (from FIG. 3-1)
1110
175
3309
GRAND TOTAL CADMIUM CONTAMINANTS
1425
175
4140

Source: Derived by SRI from multiple sources

FIGURE 3-2 INCIDENTAL CADMIUM DISPOSAL QUANTITIES IN THE U.S. (Metric Tons per Year)

Emissions of cadmium to the air resulting from the use of superphosphate fertilizers were calculated, assuming 11 million metric tons per year consumption (Ref. 3, p. 86) and the standard EPA air emission factor of 0.11 ppm. (Note that we distinguish between the use and the production of fertilizer. We have not looked into the large-scale water and land pollution problems rising from mining and beneficiating phosphate rock.)

To calculate the cadmium distributed to land by fertilizer applications, we used an average value of 8 ppm in the fertilizer, the mean of the analytical values reported by Yost at Purdue.[21] This projects to 87 metric tons per year of cadmium deposited on land by fertilizer. However, Figure 3-2 does not show the complete flow process, because cadmium does not reside inertly in the land. Its pathway to man continues by runoff to water sources and by known absorption into food grown on the land. That problem is discussed in more detail in Chapter 6, Exposures.

Combustion of 469 million metric tons of coal per year[3] with an air emission factor estimated by EPA[18] of 0.5 g of cadmium per metric ton of coal implies that 235 metric tons of cadmium annually passes through the control equipment and into the air. Cadmium also collects in the flyash that goes to landfill. To arrive at a reasonable figure for cadmium in flyash, a material balance was established using statistics from the Bureau of Mines.[22] In 1970, combustion of 469 million metric tons of bituminous coal resulted in 24 million metric tons of flyash, 9 million metric tons of bottom ash, and 2.5 million metric tons of boiler slag. However, subtracting the bottom ash and slag from an average of 10 percent total ash[23] leaves about 35 million metric tons of flyash going to electrostatic precipitators or other collectors. Comparing this residual calculation to the 24 million metric tons collected by precipitators shows an efficiency of only 68 percent--much lower than the 90-percent efficiency usually estimated for precipitators in controlled tests. The difference could be due to gradual losses in precipitator efficiency over time and to lower efficiencies of cyclone-type collectors without precipitators.

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[21] K. L. Yost, et al., "The Environmental Flow of Cadmium and Other Trace Metals," Vol. I, Progress Report, July 1, 1972 to June 30, 1973, prepared by Purdue Univ., for National Science Foundation (1973).

[22] C. E. Brackett, "Production and Utilization of Ash in the United States," pp. 12-18 in "Ash Utilization," Proc. 3rd International Ash Utilization Symposium sponsored by National Coal Assoc., Edison Electric Institute, American Public Power Assoc., National Ash Assoc., and Bureau of Mines, Pittsburgh, Penn., 13-14 March 1973, Bureau of Mines Information Circular 8640 (1973).

If we assume that the industry-wide collection efficiency for cadmium as well as total flyash is 68 percent, then 499 metric tons of cadmium remain in the collected flyash. By adding the amounts in bottom ash, slag, and gases escaping to the air, we calculate that the input cadmium concentration in coal totals 977 metric tons: a nationwide average of 2.08 ppm. This average is at the upper end of the 0.25 to 2 ppm range quoted by Fulkerson.[3]

Combustion of 1,814 million metric tons of diesel and fuel oil containing an average 0.2 ppm of cadmium adds another 36 metric tons. Estimated air emissions resulting from rubber tire wear and motor oil consumption are those reported by Davis.[15] Gasoline emissions are based on a concentration of 20 ppb, as estimated by SRI from confidential industrial sources.

Cement plant emissions are based upon the production of 70 million metric tons (124 million metric tons feed) in 1972 and escape according to the EPA emission factors, as reported by Anderson.[16] This source contributes another 32 metric tons to cadmium loading of the atmosphere.

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[23] R. F. Abernethy, M. J. Peterson, and F. H. Gibson, "Spectrochemical Analyses of Coal Ash for Trace Elements," Bureau of Mines, Report of Investigations 7281 (July 1969).

In summary, the major sources of cadmium pollution can be seen by reference to Figures 3-1 and 3-2. The major air emissions come from: (1) the roasting of ores to recover zinc, lead, and copper; (2) the recovery of scrap steel; and (3) the combustion of coal, principally in thermal electric plants. Air emissions from these sources are also important water and land contaminants from the standpoint of particulate fallout and washout by rainfall. Where surface waters are used for irrigation, some of the contained cadmium will appear in food, normally the most important source of cadmium to the human body.

Direct deposition of cadmium onto the land accounts for the largest amounts of all, but most landfill operations appear able to isolate their waste materials quite successfully. Dispersed disposal of cadmium wastes through fertilizers and, as mentioned above, deposition of contaminants from the air and water seem to present more significant problems to the land.

Illustrative Application: Asbestos

Tracing of the various paths through which asbestos enters our environment is complicated by the popularity of this material (3,000 uses according to the Asbestos Information Association of North America). Still, it seems strange that after all of the years since asbestos was found to cause cancer in industrial workers[24] and to pervade the urban environment,[25] there is still controversy over the amounts and even the sources of contamination. As a starting point, we have utilized the product categories outlined by the U.S. Bureau of Mines[26] to attempt to isolate the major suspected sources.

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[24] R. Doll, "Mortality from Lung Cancer in Asbestos Workers," Brit. J. Ind. Med., Vol. 12, p. 18 (1955).

[25] W. J. Nicholson, A. N. Rohl, and E. F. Ferrand, "Asbestos Air Pollution in New York City," In Proc. 2nd International Clean Air Congress, H. M. Englund and W. T. Berry, editors, Academic Press, New York, pp. 136-9 (1971).

Several investigators have pinpointed brakes and clutches as a principal source of asbestos in air.[27,28] Conversely, other micro-studies have cast doubt upon this hypothesis.[29] Spray-on asbestos insulation has been pinpointed by Selikoff[30] as a probable contributor. Obviously, air emissions from the asbestos industry itself are contributing to the pollution problem.[31] A less obvious source may be the growing practice of incinerating solid wastes containing asbestos.

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[26] R. A. Clifton, "Asbestos," Bureau of Mines, Minerals Yearbook Pre-Print (1972).

[27] C. F. Harwood, "Asbestos Air Pollution Control," PB 205238 prepared for for the Illinois Institute for Environmental Quality by the Illinois Institute of Technology Research Institute, Chicago, Ill., (November 1971).

[28] L. Bruckman, "Asbestos, an Evaluation of Its Environmental Impact in Connecticut," State of Connecticut, Department of Environmental Protection, Air Compliance-Engineering (12 March 1973).

[29] M. G. Jacko, R. T. DuCharme, and J. H. Somers, "How Much Asbestos Do Vehicles Emit?" Automotive Engineering, Vol. 81, No. 6, pp. 38-40 (June 1973).

[30] I. J. Selikoff, W. J. Nicholson, and A. M Langer, "Asbestos Air Pollution," Arch. Environ. Health, Vol. 25, No. 1, pp. 1-13 (July 1972).

[31] "National Inventory of Sources and Emissions: Cadmium, Nickel, and Asbestos--1968," (Asbestos, Section III), PB 192-252, prepared by W. E Davis & Associates, Leawood, Kansas (February 1970).

Uses of Asbestos

The diversity of products is illustrated by the examples given in Table 3-1; the industrial pollution resulting from the manufacture of these products, its initial transfer as solid waste, and its ultimate disposal to air, water, and land sinks are summarized in the flowsheet in Figure 3-3. Besides the products listed individually, several large uses including calking, roof coating, and auto undercoating are grouped under "Other."

Air emission factors used to calculate the pollution resulting from each manufacturing category are from Anderson.[18] Water pollution factors were taken from a Booz-Allen report.[32] Landfill factors, mainly manufacturing wastes and rejects, were assumed here to comprise 0.5 percent of production, going to landfill. These product breakdowns help to trace flow patterns to final air, water, and land disposal, although their annual variations are not available.

Disposal of Asbestos

Airborne asbestos should ultimately settle out or be washed from the air by rainfall, but its path is circuitous because of refloatation brought about by wind and human activities, such as transportation. Therefore, we can obtain better estimates of the quantities of asbestos entering the biosphere than we can of the quantities already present. The solid waste factor of 0.5 percent for fabrication of asbestos construction products sends 1,536 metric tons per year to solid waste disposal. Other production wastages calculated in the reports mentioned above send smaller amounts to air and water (see Figure 3-3).

During construction, asbestos lost to the air totals 54 metric tons per year under the EPA emission factor assumptions.[18] But most asbestos

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[32] "A Study of Hazardous Waste Materials, Hazardous Effects and Disposal Methods," Vol. III, PB 221 467, prepared for U.S. Environmental Protection Agency by Booz Allen Applied Research, Inc. (1973).

Table 3-1

THE USES OF ASBESTOS

Asbestos - Cement Industry

- Shingles for roofing and siding
- Wall sheets
- Insulation board
- Clapboard
- Electric motor casings
- Water and sewage pipes
- Gas pipes
- Rain gutters
- Air ducts
- Refuse chutes

Asbestos - Textile Industry

- Fireproof theater curtains
- Lagging
- Other insulation wrapping
- Conveyor belting
- Safety clothing
- Potholders
- Ironing board covers
- Draperies
- Rugs
- Motion picture screens
- Gas filters in gas masks
- Filters for processing fruit juices
- Filters for processing acids
- Filters for processing beer
- Filters for processing medicine
- Mailbags
- Prison-cell padding
- Airplane fittings
- Stove and lamp wicks
- Sparkplugs
- Fire hose

Electrical Equipment Industry

- Insulation tape

Asbestos Papers, Felts, and Millboard

- Roofing
- Piano padding
- Stove and heater linings
- Filing cabinet linings
- Military helmet linings
- Automobile hood mufflers
- Boiler jackets
- Radiator covers
- Acoustical ceilings
- Plasterboard
- Fireproof wallboard
- Electrical switch boxes
- Safes
- Table pads
- Stove mats
- Ovens
- Dry kilns

Asbestos Plastics

- Flooring tiles (asphalt and vinyl binders)
- Reinforcement and filler in plastics
- Plastic products (frying-pan handles, rocket nose covers)

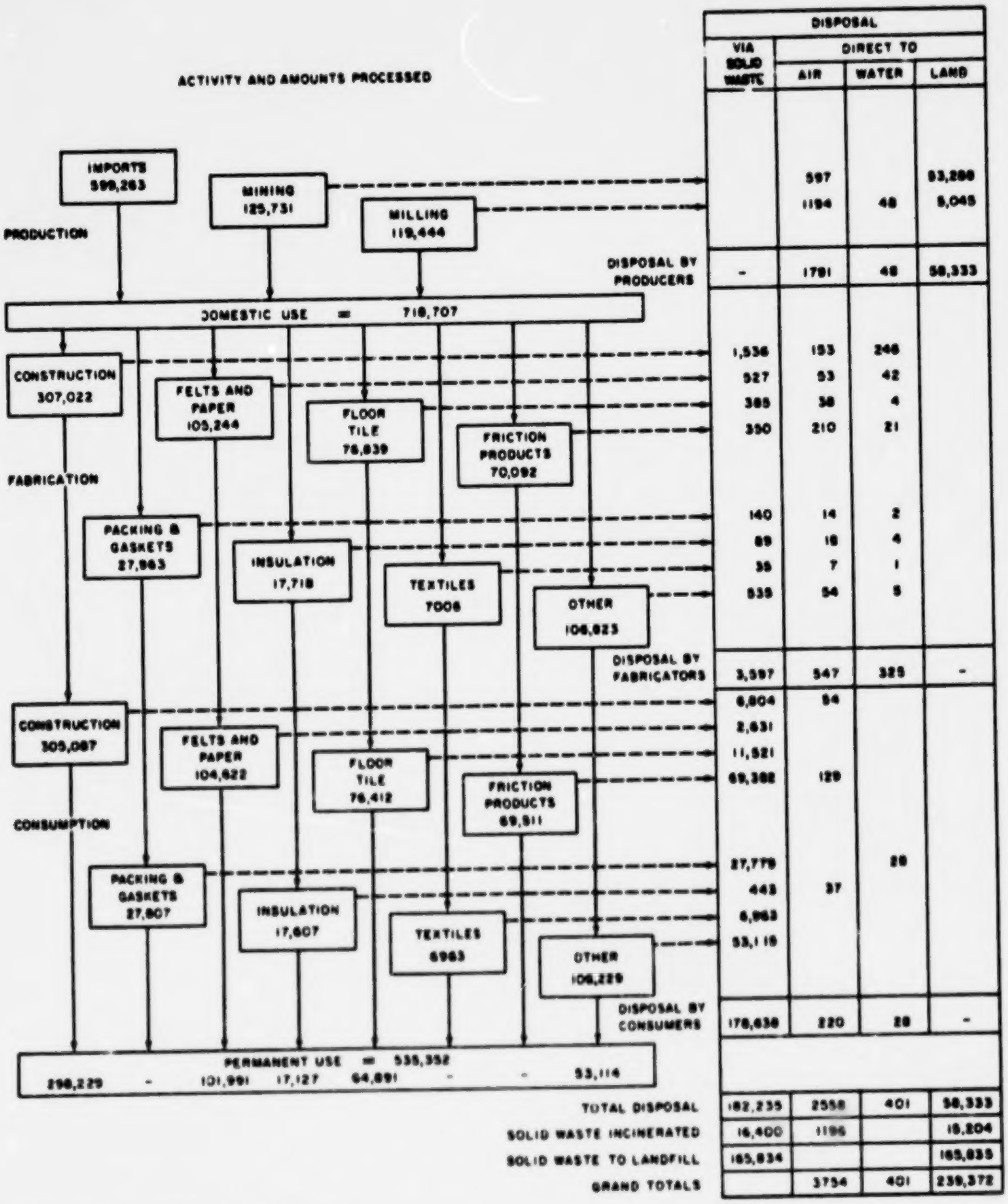
Miscellaneous

- Ingredient of paints and sealants
- Component of roof coating and road-building compounds
- Putty, calk, and other crack fillers
- Artificial snow
- Spray insulation on structural steel
- Undercoating on automobile bodies
- Gaskets and packing materials
- Insulation materials

Friction Materials

- Brake linings
- Clutch facings

Source: Bruckman, 1973


ACTIVITY AND AMOUNTS PROCESSED
PRODUCTION
IMPORTS 599,263
MINING 125,731
MILLING 119,444
DOMESTIC USE = 718,707
FABRICATION
CONSTRUCTION 307,022
FELTS AND PAPER 105,244
FLOOR TILE 76,839
FRICTION PRODUCTS 70,092
PACKING & GASKETS 27,963
INSULATION 17,718
TEXTILES 7006
OTHER 106,823
CONSUMPTION
CONSTRUCTION 305,087
FELTS AND PAPER 104,622
FLOOR TILE 76,412
FRICTION PRODUCTS 69,911
PACKING & GASKETS 27,807
INSULATION 17,607
TEXTILES 6963
OTHER 106,229
PERMANENT USE = 535,352
298,229
-
101,991
17,127
64,891
-
-
53,114
DISPOSAL
VIA SOLID WASTE
DIRECT TO
AIR
WATER
LAND
597
53,288
1194
48
5,045
DISPOSAL BY PRODUCERS
-
1791
48
58,333
1,536
153
246
527
53
42
385
38
4
350
210
21
140
14
2
89
18
4
35
7
1
535
54
5
DISPOSAL BY FABRICATORS
3,597
547
325
-
6,804
54
2,631
11,521
69,382
129
27,779
28
443
37
6,963
53,115
DISPOSAL BY CONSUMERS
178,638
220
28
-
TOTAL DISPOSAL
182,235
2558
401
58,333
SOLID WASTE INCINERATED
16,400
1196
15,204
SOLID WASTE TO LANDFILL
165,834
165,835
GRAND TOTALS
3754
401
239,372

Source: Derived by SRI from multiple sources.

FIGURE 3-3 ASBESTOS PRODUCTION, FABRICATION, CONSUMPTION, AND DISPOSAL QUANTITIES IN THE U.S. (Metric Tons per Year in 1972)

construction materials are installed in "permanent" uses lasting 40 or more years, such as commercial and industrial buildings and pipelines for water, steam, sewage, and gas. These uses imply a demolition rate of about 2.5 percent (or 6,804 metric tons) per year going to solid waste disposal (see Figure 3-3 and Table 3-2).

As with our cadmium consumption model, 91 percent of the solid waste goes to landfill. Only 9 percent goes through an incineration process, half in controlled municipal incinerators and half in uncontrolled processes. However, since construction asbestos is nonburnable and normally tightly bound, we estimate that only 1 percent of the amount processed reaches the stacks. Thus, about 450 grams of asbestos for each metric ton demolished goes to the stacks of uncontrolled incinerators, and another 450 grams goes to controlled incinerators. Scrubbers

Table 3-2

FACTORS USED TO CALCULATE THE ULTIMATE DISPOSAL OF ASBESTOS

	Percent to Consumer Use	Annual Percent of Consumer Use Disposed as Solid Waste	Percent of Disposed Solid Wastes Released to Incinerator
Construction	97.1%	2.5%	1%
Felts and paper	96.9	2.5	60
Floor tile	49.4	15	10
Friction products	0	100	10
Packing and gaskets	0	100	10
Insulation	96.7	2.5	60
Textiles	0	100	50
Other uses	49.7	50	10

Source: Estimated by SRI

remove 80 percent of even this small amount from most municipal incinerators, so the total construction asbestos escaping to the air from both controlled and uncontrolled incinerators is only about 540 grams for each metric ton demolished in old construction. A negligible amount (in the order of 0.5 percent of the amount escaping to the air) is emitted to cooling water for the ash.

Disposal estimation is similar for most other product lines, as summarized in Table 3-2. However, several pollution factors fall outside the standard methodology. Emissions from brake linings ("Friction Products" in Figure 3-3) were calculated using an EPA emission factor given by Anderson).[18] Likewise, EPA emission factors provide estimates of air emissions in the insulation and construction product categories. We estimate the erosion of pump packings into consumer products to be 0.1 percent per year, mainly through water media.

Asbestos air pollution from municipal incinerators amounts to hardly 5 percent of total emissions from all mining, milling, fabrication, and disposal operations. The predicted emissions of 200 metric tons from all municipal incinerators amount to an emission factor of 15 grams of asbestos per metric ton of solid waste incinerated, based upon an annual rate of solid waste incineration of 15 million metric tons per year. The reasonableness of these figures is difficult to establish, since we could find no reported values for the asbestos content of the stack gases from municipal incinerators.

We do know that the 15 grams per metric ton asbestos emission estimates are at least 1 to 2 orders of magnitude lower than total incinerator particulate emissions. An asphalt roofing material in an experimental multiple chamber incinerator without controls gave minimum total particulate emissions of 1,300 g/metric ton charged.[33] If emission controls to remove 80 percent of the particulates had been used, these experiments would have emitted at least 260 grams of total particulates per metric ton of solid waste.

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[33] R. L. Stenburg, et al., "Effects of High Volatile Fuel on Incinerator Effluents," J. Air Poll. Control, Vol. 11, No. 8, pp. 376-383 (August 1961).

Comparisons may also be made with asbestos air concentration levels in other environments. If the model incinerator discharges 0.044 gram of asbestos and 64 standard cubic meters of air per second, the asbestos concentration will be 742 micrograms per cubic meter. The proposed OSHA standard for air in working spaces (2 fibers/cm^3 greater than 5 microns) is roughly equivalent to 24 μg/m^3*, or one-thirtieth the estimated incinerator stack concentration.

Visually observed industrial exposures as high as 18 fibers/cm^3 are reported in U.S. mines and mills.[34] This converts to 216 μg/m^3, a value about one-third as high as the calculated incinerator air concentration. All of these comparisons indicate that our estimates of incinerator emissions are at least in the right order of magnitude.

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[34] L. A Schutz, W. Bank, and G. Weems, "Airborne Asbestos Fiber Concentrations in Asbestos Mines and Mills in the United States," Bureau of Mines Health and Safety Program, Technical Progress Report No. 72 (June 1973).

*The OSHA concentration is easily derivable from Bruckman's[35] observation that for every fiber longer than 5 microns counted by the standard visual "phase-contrast illumination" method, there are actually 50 fibers countable by the electron microscope method, and from his conversion factor of 1,000 fibers observable by the electron microscope method per nanogram of asbestos. Occupation exposures are based on an 8-hour day and 5-day week, which must be converted to equivalent continuous exposures. The OSHA standard in terms of a full-time air concentration is thus:

$$\frac{2\ \text{fibers}}{\text{cm}^3} \times 50 \times 10^6\ \frac{\text{cm}^3}{\text{m}^3} \div 1000\ \frac{\text{fibers}}{\text{nanogram}} \times \frac{8}{24} \times \frac{5}{7} = 24 \times 10^3\ \frac{\text{ng}}{\text{m}^3}$$

[35] L. Bruckman and R. A. Rubino, "Rationale Behind a Proposed Asbestos Air Quality Standard," No. 74-222. presented at the 67th Annual Meeting of the Air Pollution Control Association, Denver, Colorado. 9-13 June 1974.

Overall, we may conclude from these estimates that incinerators could be significant but far from predominant in causing asbestos air pollution in the United States. Mining, milling, and manufacturing facilities each produce much larger quantities. Furthermore, the diverse and widespread presence of asbestos throughout our society, its consumptive use in such applications as automobile brakes, and its persistence in the biosphere makes it a much more pervasive pollutant than cadmium. For these reasons, it seems less easy to control by means short of restricted usage, and it offers only marginal gains for any particular control strategy.

Chapter 4

ALTERNATIVE CONTROL COSTS AND EFFECTIVENESS

Introduction

This chapter is devoted to an examination of several alternative means of reducing pollution in the processes described in Chapter 3, and the costs of these alternatives.

Background

One of the conveniences of working with the contaminant flow system defined in Chapter 2 and developed in Chapter 3 is that it helps to specify various types of pollution control activities and relate them to each other. Each type of control can be physically described since, as Figure 2-1 implies, a control is any set of personnel, equipment, and operational procedures that can act to restrict contaminant flows.

The control can be defined in various ways, depending upon how broad a part of the contaminant flow system is being covered and how the control operates. Useful operating distinctions can be made, for example, among controls that are primarily active (such as limestone scrubbers), primarily passive (tall stacks), and primarily restrictive (regulations over the permissible uses of asbestos). Each of these types of control methods requires a different mix of personnel, equipment, and operating resources, and each will be most feasible in different situations, so their indicated costs and effectiveness can vary widely with the assumed operating conditions. Therefore, it is necessary to be selective in assessing the appropriate range and application of control alternatives.

Specifications

In this study, only a few alternative controls have been chosen to illustrate how their choice interacts with the process of standard setting. These alternatives have been chosen because they appear potentially significant to the cadmium and asbestos pollution flows described in Chapter 3, and because they are either now operational or well enough developed so that sufficient data exist for cost and effectiveness analyses. In accordance with the research objectives of the project, they all could cause significant changes in land disposal volumes, although in a larger sense they can better be evaluated in the multimedia framework of Chapters 2 and 3 than in terms of land (or water or air) alone.

Inasmuch as the above criteria are somewhat restrictive and the objective of the procedure is to illustrate a new methodology rather than to address any particular current policy issue, the alternatives have not been chosen necessarily to represent the most topical, controversial, feasible, or effective of possible controls. Neither have they been chosen to encompass the conceptually similar but analytically much more difficult problems of controls for multiple contaminants and of multiple controls for individual contaminants. For these reasons, such important control issues as stack scrubbers for coal electric plants and asbestos emission controls for the construction industry are not examined in detail. Instead, we illustrate our methodology with two somewhat simpler cadmium control alternatives and two asbestos alternatives.

Cadmium Control Alternatives

The material balance analyses of the previous chapter provide a good basis for developing potential cadmium control alternatives, since they indicate the largest sources of contamination in air, water, and land. For example, Figure 3-1 shows that the largest volume of cadmium air contaminants comes from refining operations, with zinc refining the dominant contributor. The third largest volume of cadmium air contamination, as well as the second largest volume of water pollution, comes from incinerator operations in solid waste disposal. Controls are examined for these two operations. Other large contaminating activities such as remelt steel to air and sewers to water are not assessed here.

A. Proposed Control for Zinc Smelters

Although zinc smelters represent obvious emitters that might be controlled, their high contaminant outputs do not directly provide the information needed for risk/benefit analysis. We also need to know the amounts of non-health benefits foregone by imposition of controls, the dispersion patterns of the contaminants, the effects of the resultant contamination levels on human health, and the number of people affected. These factors are quantified in Chapters 5, 6, and 7 below. But the starting point for all of these analyses is specific technical information about the contaminants emitted. Since higher volume smelters will emit more cadmium, a knowledge of production by plant is required.

In Table 4-1, we list the Bureau of Mines[38] breakdown of smelter capacities for 1972. An estimate of the cadmium production rate of each smelter is computed by using an average rate of 4.4 kg of cadmium produced per metric ton of zinc capacity (Ref. Fulkerson). Air emissions are then calculated using the Fulkerson ratio of 0.205 units of cadmium emitted for each unit produced. The 1972 production of 3,542 metric tons calculated in this manner compares closely with the reported 1972 production of 3,760 metric tons. For modeling purposes, we define

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[38] A. D. McMahon, J. M. Hague, and H. R. Babitzke, "Zinc," in Bureau of Mines Minerals Yearbook, pp. 1299-1333 (1972).

Table 4-1

ESTIMATED AIR EMISSIONS OF CADMIUM FROM ZINC SMELTER OPERATIONS IN 1972

Plant Location	Zinc Capacity (metric tons/yr)	Cadmium Production (metric tons/yr)	Cadmium Air Emissions (metric tons/yr)
Corpus Christi, Texas	50,000	220	45
Amarillo, Texas	74,000	327	67
Sauget, Illinois	76,000	335	69
Blackwell, Oklahoma	58,000	255	52
Bartlesville, Oklahoma	45,000	200	41
Monaca, Pennsylvania	214,000	941	193
Palmerton, Pennsylvania	195,000	858	176
Bunker Hill, Idaho	92,000	406	83
Total	804,000	3,542	726
Average	100,500	443	91

Source: Bureau of Mines, 1972

the average zinc smelter as producing 100,000 metric tons of zinc and 440 metric tons of by-product cadmium per year and emitting 90 metric tons per year of cadmium.

In Table 4-2, estimates of limestone scrubber emission controls for the model zinc smelter are given in terms of operating effectiveness, investment cost, and annualized cost. Values of sulfur dioxide emissions are given for reference because several analytical studies, experimental programs, and actual operating installations have been implemented to evaluate the SO_2 emissions problem. Studies sponsored by EPA[37] estimate

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[37] D. A. LeSourd and F. L. Bunyard, "Comprehensive Study of Specified Air Pollution Sources to Assess the Economic Impact of Air Quality Standards," Vol. 1, PB-222 857, prepared for the U.S. Environmental Protection Agency, Division of Effects Research by Research Triangle Institute (August 1972).

Table 4-2

MODEL ZINC SMELTER CONTROL COSTS AND EFFECTIVENESS

Production, zinc	100,000 metric tons/yr
Gas volume to scrubbers	49 standard m^3/sec
SO_2 concentration in gas	787 g/m^3
Cadmium concentration in gas	84 mg/m^3
Cadmium emissions (continuous equivalent)--uncontrolled	4.1 g/sec
Cadmium emissions (continuous equivalent)--95% controlled	0.2 g/sec
Investment (approximate 1970 prices)	
Flue gas modification	$1.99 million
Limestone grinder	2.88
Gypsum storage, disposal	0.28
Scrubber	1.20
Site preparation	0.62
Offsite facilities	0.62
Total investment	$7.59 million
Annual Cost	
Labor	$0.079 million/yr
Power	0.720
Limestone	1.555
Water	0.408
Maintenance	0.182
Depreciation	0.505
Interest, taxes	0.759
Total annual cost	$4.208 million/yr

Source: Lesourd (see Ref. 37).

that limestone scrubbers can reduce SO_2 and particulate emissions by about 95 percent. We adapt this estimate for cadmium particulate emissions.

The annualized cost for each model smelter is $4.2 million, so the cost for eight "average" model zinc smelter controls, approximately $33.6 million, can be taken as the total annual national cost. In addition, one should estimate the governmental costs for direct monitoring or at least occasional verification of plant self-monitoring activities, enforcement of compliance, and administrative overhead. These government enforcement and administrative costs can be significant, but we could find no prior control analysis in which they were explicitly added as a cost consideration. We were therefore forced to resort in this study to a rough estimate based on generalized expenditure data. Our estimate uses an average comparison of essentially all operational costs for pollution control in the country with government administrative and overhead budgets for pollution control.

Outlays for pollution control operational costs in the United States amounted to $10.4 billion in 1970, excluding monitoring and enforcement.[38] Only about $0.3 billion of these costs were federal, leaving $10.1 billion nonfederal ($4.6 billion state and local, and $5.5 billion private). Expansion of operational control costs was projected to expand to 1980 at about 10 percent per year in constant dollars, so that total 1972 operational pollution control costs would be $12 billion.

Enforcement and administrative costs by the federal government totaled $1 billion in 1972--about half of the $1.975 billion reported for all federal pollution control and abatement activities (see Reference 38, Table 5-1). This $1 billion went for administrative support of state and local pollution control organizations, for research and development, and for federal pollution control activities. (The other half went mainly for grants to municipal sewage treatment plants and for pollution control operations at federal facilities.) Add a modest amount of unreimbursed enforcement costs by state and local governments to the $1 billion federal total, and the total could easily reach 10 percent of the $12 billion direct operational expenditures in 1972. This estimate of 10 percent excludes such overhead expenses as the legal and administrative costs of compliance and reporting that are borne by regulated facilities, and the court costs of any litigation. Nevertheless, a 10-percent add-on to operational costs for enforcement does seem consistent with the level of administrative burden that might be expected in government regulatory programs, and will be accepted here in the absence of more precise data. Thus, the annualized national costs for operation and enforcement of zinc smelters controls will be 110 percent of $33.6 million, or $37.0 million.

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[38] Environmental Quality, Third Annual Report of the Council on Environmental Quality, GPO, Washington, D.C. Table 1 (August 1972).

Finally, we must estimate the variability of all these estimates. The two-sigma confidence limits (encompassing 96 percent of the anticipated outcomes) are approximated on the basis of developmental prospects and rather limited operational experience. They can be represented by a single factor with which to multiply or divide the mean estimate. Use of this type of confidence limits permits us to accommodate wide uncertainties and also to combine different components to derive an overall uncertainty. For the effectiveness estimate, the factor we use is 1.05. When multiplied by our mean estimate of 0.95, it yields an upper confidence limit of 0.9975, and when divided into the mean, yields a lower confidence limit of 0.905. For statistical calculations, this is expressed as a lognormal variable with a mean of log 0.95 and a standard deviation of ± log 1.025.

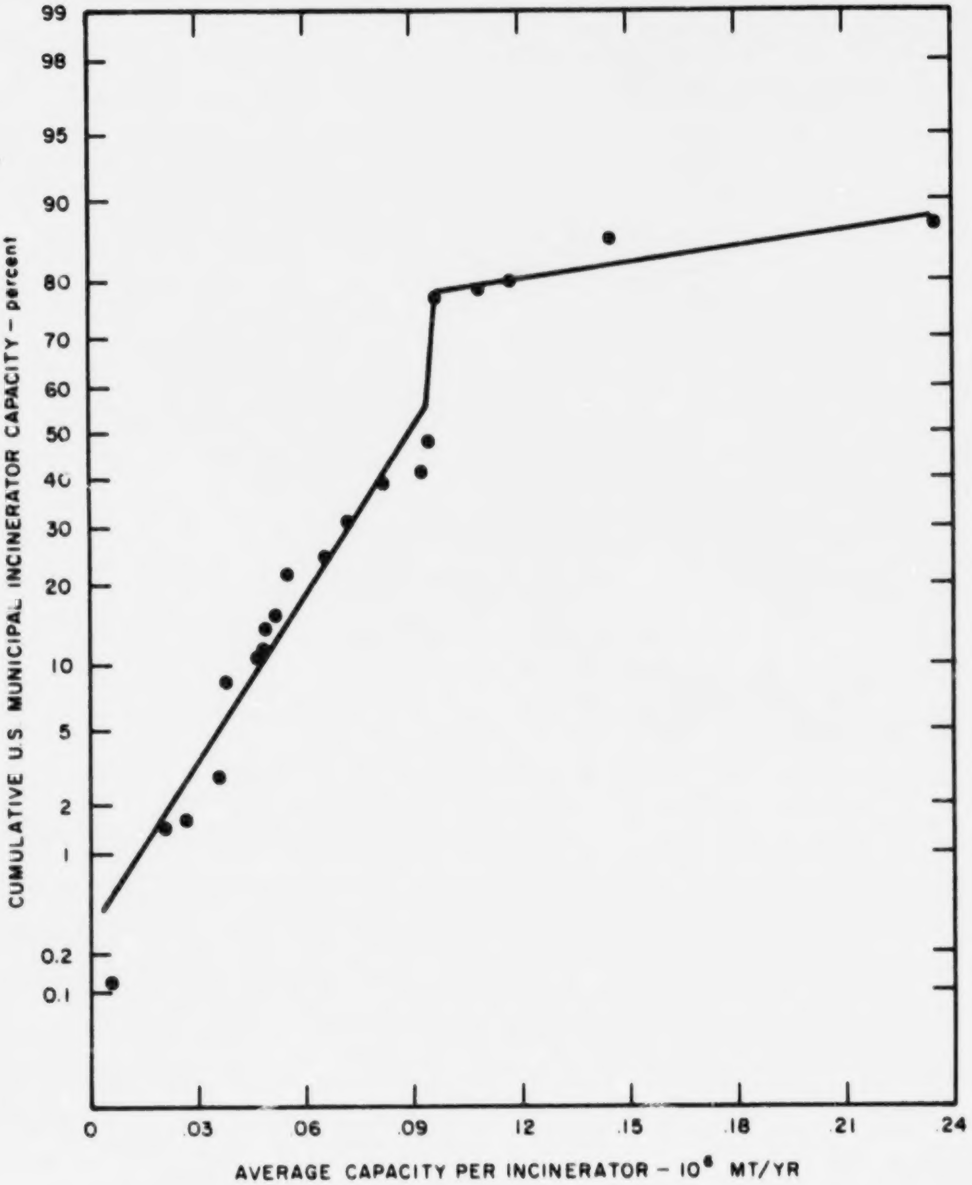
Cost estimates are also expressed with confidence limits. We ignore uncertainties that may arise strictly from cost inflation because these costs can be approximately adjusted by applying an appropriate inflation index or by reestimating. Two-sigma limits due to inherent uncertainties in cost estimating procedures we evaluate as ± a factor of 1.2 (i.e., a range from 83 percent to 120 percent of the estimated costs). The log-normal expression for this variable is: mean = log 1 = 0, sigma = log 0.1. Variability in enforcement costs can be neglected, since these are an order of magnitude smaller than the operational costs and very unlikely to be important.

A Proposed Control for Solid Waste Incinerators

A national incinerator inventory conducted by the Office of Solid Waste Management showed that only 193 municipal-scale incinerators were operating in 1972, compared to 251 in 1969. Figure 4-1 gives in ascending order the average incinerator size for each of the 22 states covered in that survey. The overall national average size is 0.096 million metric tons per year capacity, near a discontinuity in the curve.

Locations of existing municipal incinerators are also significant because most are in the heavily populated northeastern quarter. In fact, 153 of the operating incinerators are located in that area, and EPA has disclosed that 90 are in a narrow Atlantic seaboard area known as the Incinerator Belt. That belt contains 13 percent of the nation's population, as well as almost one-half of the total operating incinerators, but only 0.06 percent (4,600 km^2) of the land area (see Achinger, Reference 17).

The material balance of cadmium disposed to solid wastes, summarized earlier in Figure 3-1, shows that 31 metric tons of cadmium air emissions come from solid waste incinerators. Only a fraction of this total comes from municipal plants. Based on an EPA emissions factor of 0.4 gram



SOURCE: DERIVED BY SRI FROM ACHINGER

FIGURE 4-1 MUNICIPAL INCINERATOR AVERAGE CAPACITIES BY STATE

cadmium per metric ton burned[18] and an estimated 15 million tons incinerated, the total cadmium air emission from municipal incinerators amounts to 6 metric tons per year. The remainder comes from open burning, industrial incinerators, commercial scavengers, and John Q. Citizen burning wastes in his back yard and fireplace. Control of municipal incinerators can therefore have only a minor impact on the total solid waste incineration problem in most communities.

Table 4-3 gives the costs to control air emissions from municipal incinerators of various sizes; Table 4-4 summarizes the operating scrubbers on a medium-size (263 metric tons per day) municipal incinerator model. No water pollution control cost data are given for these incinerators, since most water is discharged to municipal sewer systems already operating. However, we should note that the cadmium concentration shown for effluent water from the model incinerator (0.126 mg per liter) is more than 10 times over the acceptable concentration (0.01 mg/liter) for drinking water standards.

Annualized scrubber control costs for the model incinerator are given as $110,000, in 1972 prices; an additional 10 percent for enforcement costs brings the total to $121,000 per year. Uncertainties in those cost estimates are proportionately the same as the aforementioned uncertainties for zinc smelter scrubber costs. The lognormal value of sigma is log 1.1, and the upper and lower two-sigma confidence limits are, respectively, 0.83 and 1.20 times the mean $110,000 cost estimate. The mean estimated control effectiveness is 0.85 (see Table 4-3). The upper confidence limit is taken here as the mean multiplied by a factor of 1.15 (0.98), and the lower confidence limit is the mean divided by 1.15 (0.74). The corresponding lognormal expressions are: mean log 0.85, sigma log 1.075.

Table 4-3

MUNICIPAL INCINERATOR CONTROL COSTS FOR EFFLUENT GASES

Size (metric tons/day)	Flue Gas Volume (m^3/sec)	Particulate Collection Efficiency (%)	Installed Cost ($1000)	Annualized Cost ($1000)
91	0.022	85%	52	39
181	0.044	85	100	77
263	0.064	85	145	110
454	0.096	90	250	172
635	0.116	95	350	213
907	0.165	95	480	302

Source: Research Triangle Institute

Table 4-4

MODEL MUNICIPAL INCINERATOR

Operational capacity	263 metric tons/day
Particulate emissions	2.01 metric tons/day
Gas volume to scrubbers	64 m^3/sec
Water volume to sewer	2.1×10^6 liters/day
Ash weight to landfill	105 metric tons/day
Cadmium concentration in effluent gas	18 $\mu g/m^3$
Cadmium concentration in water effluent	126 μg/liter
Cadmium concentration in ash	11 g/metric ton ash
Cadmium emissions (continuous equivalent)--uncontrolled	11×10^{-4} g/sec
Cadmium emissions (continuous equivalent)--85% controlled	1.7×10^{-4} g/sec

Source: Research Triangle Institute

Asbestos Control Alternatives

Lack of knowledge of the causes of asbestos pollution in the urban environment makes it difficult to suggest control strategies. Overall, the asbestos concentrations found in industrialized urban centers such as Philadelphia do not appear, from the dose/damage relationships developed in Chapter 7, to be highly deleterious to human health. However, emissions from point sources, such as factory ventilators, do present a danger to those living in the vicinity. Other more dispersed sources, such as automobile traffic, also present a possible hazard to the large numbers of people who are exposed to them. These two types of emissions and their associated costs are assessed here.

Table 4-5 shows the major industrial sources of asbestos emissions, as derived from several references. It also shows figures on numbers of plant facilities and values of annual product for each industry; these data are used to help estimate the relative asbestos emissions of each industry. Also shown is the density of the average surrounding city populations for each industry; the density data can be used in combination with the diffusion model in Chapter 6 to derive estimates of the populations at risk.

Differences in emissions data reported in the literature proved unusually difficult to reconcile. To aid in establishing reliability, we compared emissions data from our report (which was derived principally from Anderson's work for EPA[18]) with data from RTI[39] and from ADL[40]. Total annual emissions estimates for the five comparable product groups

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[39] R. E. Paddock et al., "Comprehensive Study of Specified Air Pollution Sources to Assess the Economic Impact of Air Quality Standards," Vol. II, "Asbestos, Beryllium, Mercury," PB-222 858, prepared for U.S. Environmental Protection Agency by Research Triangle Institute (August 1972).

[40] "Impact of Proposed OSHA Standard for Asbestos," First Report to U.S. Department of Labor, Arthur D. Little, Inc., No. C-74413 (28 April 1972), Appendices (5 July 1972).

Table 4-5

ASBESTOS PRODUCTS INDUSTRY AIR EMISSIONS AND SURROUNDING POPULATIONS

Product Group	Total Emissions (Metric Tons/Year)	Number of Plants	Product Value ($million/year)	Surrounding Population Density (People/km^2)
Construction	153	48	143	1,720
Floor tile	38	18	37	2,960
Friction products	210	30	203	2,507
Paper and felt	53	29	6	1,687
Textiles	7	34	10	2,203
Gaskets, packing, and insulation	32	300	351	2,800
Other uses	54	200	59	2,300
Totals	547	659	809	2,374 average

Sources: Derived by SRI from multiple sources amounted to 461.3 metric tons in our report, 595.1 in the RTI report, and 349.2 in the ADL report. We have not resolved the bases of these disagreements but accept the Anderson data partly because its total is intermediate between the totals of the other two sources. (The calculated lognormal mean of the three estimates is 458.)

The multiplying factor corresponding to the lognormal value of sigma for the three estimates is 1.31, so we estimate that the upper two-sigma confidence limit for our estimate corresponds to 461.3 x 1.31 x 2 = 746, and the lower confidence limit corresponds to 461.3 ÷ (1.31 x 2) = 285.

Fabric filters have been found to be the most effective method to control asbestos emissions from manufacturing processes and are now in proven use in some segments of the asbestos industry, as reported by Paddock. This technique has only limited application to mining processes, which are not considered here. According to EPA[41], filters can limit asbestos fiber concentrations (counting fibers longer than 5 microns) to fewer than $0.5/\text{cm}^3$ of exhaust air (equivalent to weight concentrations of less than $25{,}000\ \text{ng/m}^3$). This standard is at the lower limit of detection by the optical microscope analytical method employed for asbestos measurements. Therefore, the currently proposed limit of 2 fibers/cm^3 (four times higher) appears technically feasible for effluent air streams from asbestos factories.

The effectiveness of control of asbestos milling emissions has been estimated as 96 percent[32] on the basis of a confidential on-site plant survey. Control levels are proportionately the same for different plant sizes. Therefore, we assume that variations of control effectiveness with size are negligible, but that variations from other causes amount to a confidence multiple of ±1.03 (i.e., the two-sigma range extends roughly between 93 percent and 99 percent).

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[41] "Control Techniques for Asbestos Air Pollutants," U.S. Environmental Protection Agency, Office of Air and Water Programs, AP-117 (February 1973).

Paddock also indicates that variations in control cost are proportionate to variations in size of plant for each industry. Unfortunately, this relationship cannot be used to derive a planning factor for control costs because control costs are not proportionate to plant size when compared among different industries. (Table 4-6 shows that textile plants are more than 50 times as expensive to control as friction product or gasket plants.) Therefore, we consider only the total costs of controlling all asbestos plants, which Table 4-6 shows to be $6,946,000. By assuming that the service life for control equipment is 10 years and that annual operational and maintenance costs, interest, insurance, and taxes

Table 4-6

ASBESTOS PRODUCTS INDUSTRY CONTROL COSTS (1970 DOLLARS)

Product Group	Investments ($1,000)	Annualized Costs ($1,000)	(Annualized Costs) ÷ (Product Value)
Construction	$2,400	$ 720.	.005
Floor tile	216	64.8	.002
Friction products	720	216.0	.001
Paper and felt	348	104.4	.002
Textiles	1,700	510.	.052
Gaskets, packing, insulation	1,169	350.8	.001
Other uses	393	117.8	.002
Totals	$6,946	$2,083.8	

Sources: Paddock[33] (first five product groups)
SRI (last two product groups)

together amounted to 20 percent of the original investment, we convert this to a national annualized cost of $2,084,000 per year in 1970 dollars.

Monitoring of plant asbestos concentrations represents a significant additional cost. EPA has estimated that the cost of determining the asbestos content of sprayable insulation material by electron microscope is in the range of $300 per sample.[42] Air sampling and subsequent analysis is even more expensive. Based upon an instrument cost of $100,000 and a life of 10 years with 2 or 3 man-days per analysis* the cost of analyses for air sampling will probably be in the range of $700 per sample. The national cost of surveying 659 plants once a year at this rate would total about $460,000 per year. (To sample once a month, the annual cost would be $5.5 million.)

The national control and monitoring costs (one air sampling per year), then, would add to slightly more than $2,600,000. A 10-percent supplemental cost for enforcement runs the total national bill to about $2.9 million per year. We assume for purposes of the study that these entire costs should be included in the analysis.

To analyze variability, investment cost figures should be broken down into several segments. The purchase price of fabric filters may vary by ±20 percent.[41] Installation costs have a mean of 180 percent of purchase cost, with a low of 150 percent and a high of 200 percent; so the variability in terms of installed cost is lower than ±20 percent. These estimates do not take into account differences in the cost of capital among firms (smaller firms often have higher charges), which could add several percentage points to the variability. Similarly, the estimates do not consider the effects of inflation since 1973, or of the potentially very large variability in monitoring costs. However, we assume in our analysis that overall confidence limits for asbestos controls, monitoring, and enforcement are obtained from multiplying or dividing by a factor of 1.2.

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[42] "Background Information on the Development of National Emission Standards for Hazardous Air Pollutants: Asbestos, Beryllium, and Mercury," APTD-1503, Office of Air and Water Programs, U.S. Environmental Protection Agency (March 1973).

*Personal communication, Dale Coulson, SRI.

Automobile Asbestos Emission Controls

A control alternative frequently proposed for asbestos is to substitute an alternative material for brake linings. Although this suggestion has been around for a long time, no satisfactory substitute has yet been found.[2] As a limiting case, we can ignore feasibility and consider the economic and health implications if such a substitute were discovered.

To calculate the potential reductions by switching from asbestos brake linings, we assume that the present urban air concentration of asbestos is caused by brake linings, asbestos spray insulation, and asbestos factories, as recapitulated below from Figure 3-3.

Brakes	129 metric tons/yr
Asbestos Brake product factories	210
Asbestos Other factories	337
Spray asbestos	37
	703 metric tons/yr

If asbestos were eliminated as a brake lining, total emissions would be reduced by 339 metric tons per year. This hypothetical savings is calculated assuming the same two-sigma uncertainty factor, 1.31, as for asbestos industry emissions.

We assume that new brake materials would cost 50 percent more than asbestos brakes, that they will give equivalent wear, and that no new tooling costs will be required. The auto manufacturer's cost for asbestos brake pads is in the range of \$2.75 per set of four, so a complete set of brake linings containing new technology materials would cost \$2.75 × 1.5 = \$4.13 per vehicle. At sales of 10 million vehicles per year, the differential cost of new material brake linings would be

$$10 \times 10^6 \times (\$4.13 - \$2.75) = \$13.8 \times 10^6/\text{yr} \quad .$$

Our estimate for replacement linings is based upon a total U.S. mileage of 1×10^{12} vehicle miles per year with linings changed every 27,500 miles, so replacement linings would cost

$$36.4 \times 10^6 \text{ sets/yr} \times \$1.38/\text{set} = \$50 \times 10^6/\text{yr} \quad .$$

The total direct cost would thus be \$63.8 million per year. For an assumed 3 pounds of asbestos per brake set, the total loss in new and replacement asbestos brake linings would be 46.4×10^6 sets per year $\times$ 3 pounds per set, or 140×10^6 pounds per year. At \$211 per short ton, the lost market would be valued at \$14.8 million per year. Ten percent for government enforcement costs adds \$1.5 million. A 1.2 cost uncertainty factor (the same as for industry controls) would apply to both the lost asbestos and new substitute markets. Uncertainties about the realism of the hypothetical brake substitute are not considered.

The immediate effects of this substitution are summarized in Chapter 5. Note, however, that the benefits are long deferred behind the cost. No reasonable substitute material seems feasible at present. If a replacement lining material were available now, it would require in the range of three years to switch from marketing asbestos linings to marketing the replacement lining. The health implications of this reduction are discussed in Chapter 7.

Cost-benefit specialists will detect a slight difference between this formulation and the conventional cost-benefit approach. We split costs into two parts: the direct control costs that are covered in the present chapter and the indirect costs (or disutilities) that are included in Chapter 5. We have divided them to clearly separate the identifiable engineering and administrative costs, which are calculated by standard costing techniques, from the more speculative economic costs, which are estimated on the basis of more ambiguous and theoretically controversial economic theory.

Both types of costs are summarized in Chapter 5, but the summary is also different from a standard cost-benefit formulation. It includes positive benefits as well as costs (e.g., increased employment in the environmental controls industry) in order to compile all non-health economic effects in the cost dimension. Since the "benefits" dimension is reserved for only those benefits that are related to health, we never attempt to calculate a "cost-benefit ratio" in the conventional framework. Our approach is to a risk-benefit framework is described in Chapter 8.

Chapter 5

NET ECONOMIC BENEFITS

Introduction

It is the objective of this chapter to relate technical, cost, and production data to factors measuring economic benefits. The concern here is with the economic benefits and costs exclusive of effects on health. Nonhealth costs and benefits can then be compared with the health benefits achievable by the technically feasible controls.

In general, hazard reduction is achieved either by the introduction of specific technical controls such as air scrubbers, water cleaners, or other changes in procedures for production or use of the product or by partial or total elimination of the product. Insofar as the cost of controls affect the situation, economic factors to be considered include:

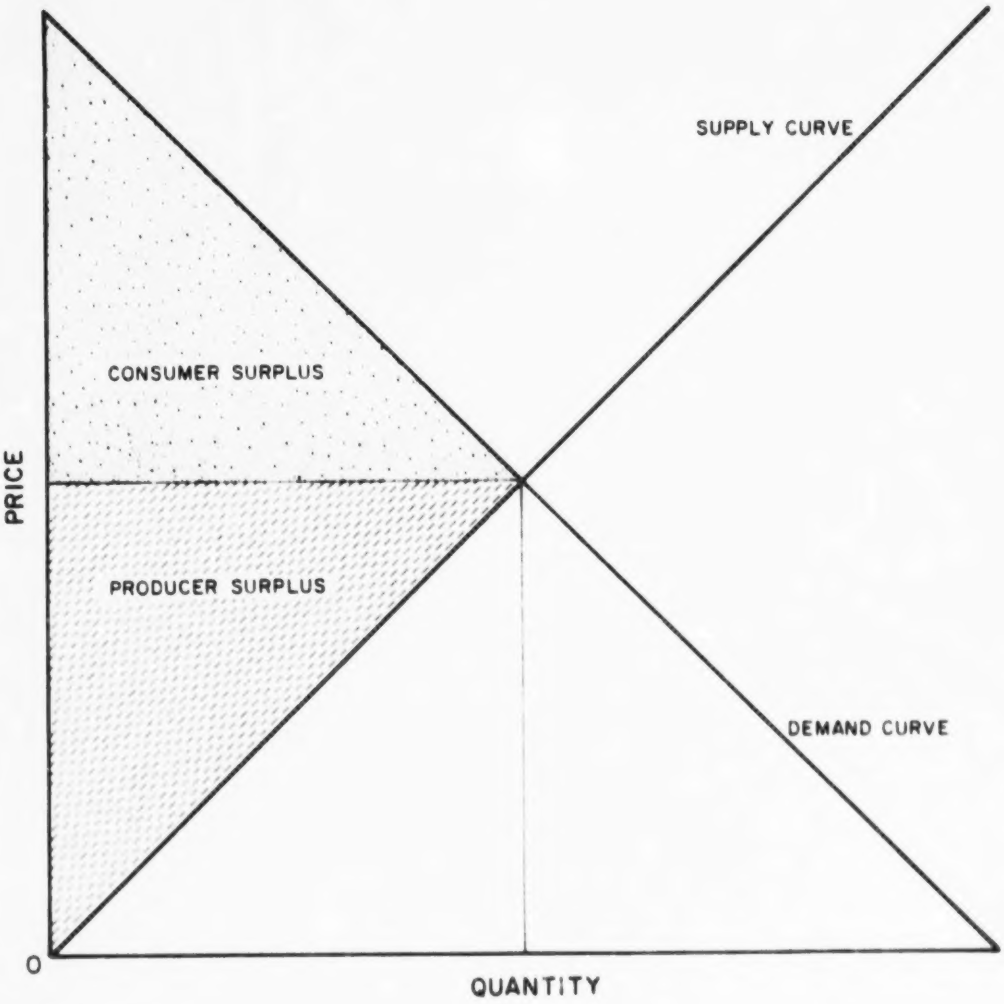
- Increased costs and price of the product.
- Reduction in producer revenues and profits.
- Possible net reduction in employment.
- Reduction of consumer benefits from the use of the product following either from its total elimination or from the reduction in consumption that follows control-induced price rises.
- Changes in net imports and the balance of trade.
- Possible adverse effects on the economies of particular regions especially affected by such changes.

This chapter, in summary, is concerned with anticipating the effects of proposed controls on these various economic variables.

Consumer Benefits

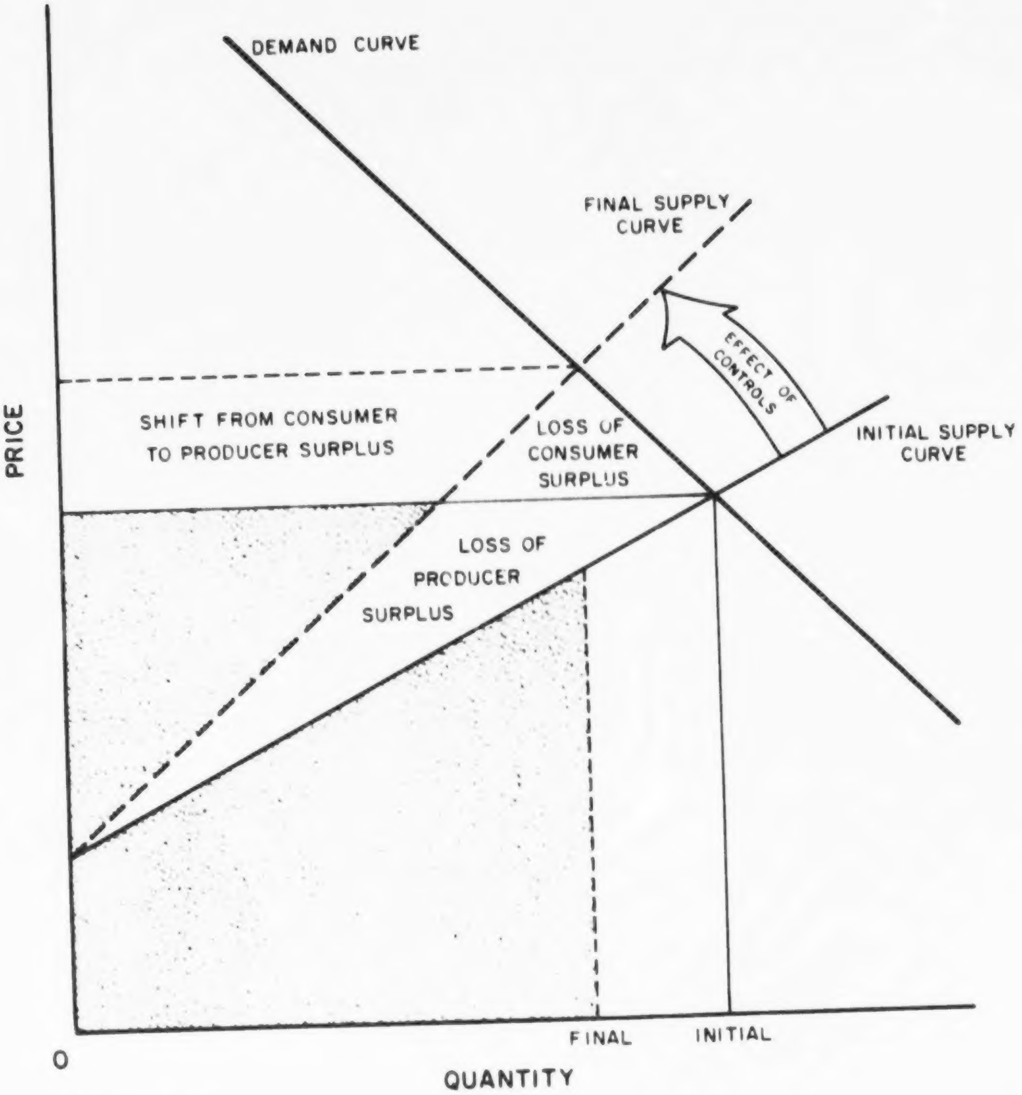
The consumer effects are usually measured by the reduction in consumer surplus, where the concept of consumer surplus has been developed in economic literature to measure an implied loss of consumer satisfaction resulting from price rises, a reduction in the quantity consumed, or both. Figure 5-1 shows the measure of consumer surplus in schematic form. Consumer surplus is by definition a value equal to the upper left triangular area in Figure 5-1. The rationale behind the consumer surplus concept concerns the difference between the actual market equilibrium price and the price that some consumers (those most eager) would have been willing to pay for the quantities they purchase. Consumer surplus measures the surplus satisfaction of these consumers. Consumer surplus is of interest here because it is generally affected by added costs resulting from controls imposed, but represents an imputed or economic welfare loss not covered by any actual cash transactions.

Figure 5-2 shows schematically the effects on consumer and producer surplus resulting from an increase in costs (such as those induced by the imposition of controls) that turns the supply curve upward and to the left. (The incremental costs induced by the imposition of controls may also raise the intercept of the supply curve; that is, the price in Figure 5-2, below which none would be supplied. This complication has been ignored to simplify the schematics, but will be allowed for in the analysis.) As shown in Figure 5-2, the loss in consumer surplus is caused by the shrinking of the triangular area that measures it when the supply curve moves upward. This loss is equal to the area of the trapezoid indicated in the schematic.



SOURCE: SRI

FIGURE 5-1. SCHEMATIC OF CONSUMER AND PRODUCER SURPLUSES


DEMAND CURVE
FINAL SUPPLY CURVE
EFFECT OF CONTROLS
INITIAL SUPPLY CURVE
PRICE
SHIFT FROM CONSUMER TO PRODUCER SURPLUS
LOSS OF CONSUMER SURPLUS
LOSS OF PRODUCER SURPLUS
0
FINAL
INITIAL
QUANTITY

SOURCE: SRI

FIGURE 5-2 SCHEMATIC: EFFECTS OF POLLUTION CONTROLS ON CONSUMER AND PRODUCER SURPLUSES

Producer Benefits

By analogy to consumer surplus, one can define as producer surplus the lower left triangular area in Figure 5-1. This measures the extra revenues received by suppliers who would have been willing to sell below the equilibrium or market price. Producer surplus is an imputed value like consumer surplus, but it is of lesser significance because actual transactions exist that better reflect producer interest, namely gross revenues, profits, and total wages. Losses to producers and wage earners can be measured directly in dollars, and such dollar valuations adequately reflect the real economic interests of business and labor. Although raising the supply curve causes a decrease in consumer surplus, it may either increase or decrease producer surplus. Because of this uncertain effect on producer surplus and the greater significance of changes in profits and earnings of the labor force, the producer surplus concept will be largely ignored in what follows.

The loss of wages occasioned by controls must be measured by loss of employment in producing the product; a loss roughly proportional to the reduction in quantity produced but offset by any increased employment in producing control equipment or associated supplies and in maintaining and inspecting the proper functioning of such equipment. Although consumer surplus is unlikely to have important interregional impacts because it is widely distributed over the population, employment effects can have a regional impact because gains in employment will be felt in the areas producing control equipment and declines will be felt in the areas producing the controlled product. Effects on profits will show similar geographic patterns, but the ultimate impacts on absentee or publicly held owners can be widely dispersed.

Trade Benefits

The balance of trade effects of imposing hazard reduction controls on domestic production depend on: (1) the vigor of foreign competition for sales of the product both domestically and overseas; (2) whether similar controls are instituted in countries supplying the competitive product; and (3) on any changes in tariff protection accorded domestic producers. For this study, it will be assumed that no added U.S. tariff is introduced and that foreign countries do not cooperate by imposing similar environmental control regulations. This results in worst-case estimates of adverse foreign trade effects. (Best-case estimates would reflect complete adjustments by tariff policies and competitive forces so as to show no change in balance of trade.)

Cadmium Examples

Cadmium Emissions and Zinc Smelter Controls

As indicated in Chapter 4, an important source of cadmium pollution arises from stack emissions from smelter processes involved in the extraction and recovery of zinc, lead, and copper from their ores. The principal sources of cadmium are by-products of such operations. A technically feasible method of control is to apply additional limestone scrubbers to clean up stack effluents. The direct effects of imposing such controls would be increases in the cost of refining zinc, lead, and copper less offsetting gains from increased amounts of cadmium recovered.

Demand and supply curves for zinc, lead, and copper cannot be well established. In the case of zinc (which involves the greatest amount of associated cadmium), gradual depletion of the high grade veins of zinc ores has led to a reduction in the number of domestic producers, a decrease in domestic output, and a consequent increase in imports. Price controls on domestic zinc were lifted in December 1973 and were followed by a substantial rise in zinc prices from about 20 cents per pound to almost 40 cents per pound. In spite of this increase, domestic suppliers have continued to decrease and have been accompanied (after a lag) by a drop in domestic consumption. Foreign prices, formerly highly competitive, have risen even higher than domestic price The decline in consumption has occurred only recently, but can be presumed to be responsive to the price increase rather than a cause of it. The decrease in domestic production, however, cannot be attributed solely to foreign competition or to increasing costs since costs do not seem to have risen as fast as price. General inflation and offsetting releases of zinc by GSA from the U.S. Strategic Stock Pile may have been significant modifying influences. The decrease in domestic production appears to be related more to the withdrawal of high cost producers from the domestic market and to a scarcity of profitable ores to be worked. The period of uncontrolled prices, however, is too short for persuasive econometric analysis.

Production Effects of Zinc Smelter Controls

Past studies of the short-run elasticity of the demand for zinc have shown it to be highly inelastic.[43,44,45,46] However the long-run demand, which is virtually impossible to derive from historical data, cannot be very inelastic in view of possible substitution of other materials for zinc in various uses and in view of past import experience. Indirect

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[43] Y. S. Hwang, "A Commodity Consumption and Export Forecasting Technique Illustrated by Zinc," Mineral Resources Branch, Dept. of Energy Mines and Resources, Mineral Bulletin MR 119, Ottawa, Canada (1971).

[44] R. G. Driver, "Econometrics and Zinc Consumption," in "Lead and Zinc, Free World Supply and Demand," 1968-71 Lead Industries Association (April 1968).

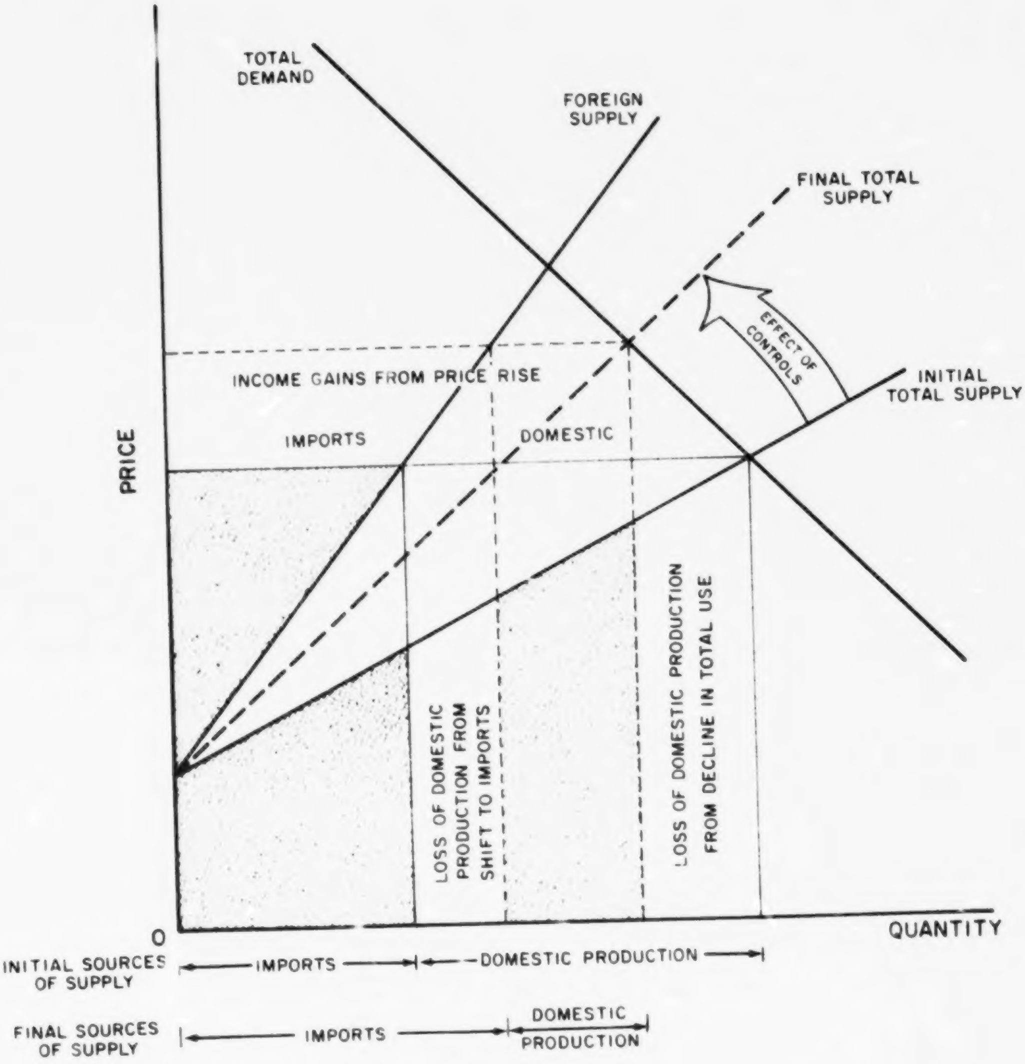
[45] F. E. Banks, "An Econometric Note on the Demand for Refined Zinc," *Zeitochrift für National ö konomic*, 31, pp. 443-452, Springer-Verlag (1971).

[46] "Lead and Zinc, Factors Affecting Consumption," International Lead and Zinc Study Group, United Nations, New York.

arguments, based on income relationships suggest that the long-run demand should have an elasticity in the range between one and two. Moreover, long-run supply should be more responsive to recent price increases than observed declines in supply would indicate. In the absence of firm empirical evidence (and some time must lapse before an adequate history of relatively free price movements can be accumulated) the long-run effects of controls on consumer surplus, producer surplus, producer profits, employment, and foreign trade can only be estimated with great uncertainty. Before attempting to discuss some plausible estimates, it may be worthwhile to discuss a schematic representation of these effects from the point of view of economic theory.

Figure 5-3 shows the market mechanisms for a product such as zinc, which is imported in substantial fraction. Here we assume that total domestic demand and both foreign and domestic supply are fairly elastic. Figure 5-3 then shows the changes in price and quantity sold both from domestic and foreign production as pollution controls are imposed on domestic production. Again, possible shifts in the intercepts of the supply curves have been ignored to simplify the schematic.

In Figure 5-3, it is assumed that no controls are imposed by foreign authorities and only the domestic supply curve is turned upward. The turn in the domestic supply curve, however, may be less than that equal to the full cost of controls because some portion of these costs might be absorbed by the producers or by government. As long as any portion of the incremental costs are passed on to the consumers (that is, as long as the domestic supply curve turns), there will be some reduction in quantity sold and in producer revenues. To anticipate the effects of controls, analysis is required of the structure of the zinc industry and the probable behavior of the domestic producers, assuming that they attempt to minimize their reduction in profits.


TOTAL DEMAND
FOREIGN SUPPLY
FINAL TOTAL SUPPLY
EFFECT OF CONTROLS
INITIAL TOTAL SUPPLY
INCOME GAINS FROM PRICE RISE
IMPORTS
DOMESTIC
PRICE
LOSS OF DOMESTIC PRODUCTION FROM SHIFT TO IMPORTS
LOSS OF DOMESTIC PRODUCTION FROM DECLINE IN TOTAL USE
0
QUANTITY
INITIAL SOURCES OF SUPPLY
IMPORTS
DOMESTIC PRODUCTION
FINAL SOURCES OF SUPPLY
IMPORTS
DOMESTIC PRODUCTION

SOURCE: SRI

FIGURE 5-3. EFFECTS OF DOMESTIC PRODUCTION CONTROLS ON FOREIGN AND DOMESTIC PRODUCERS

Although some purchases of other ores (including imports) are usual, most producers depend largely on their own sources and the lowest cost producers have access to the richer veins. High cost producers who generally must obtain ores from poorer or depleted veins, have been leaving the zinc industry. In most cases, any temporary increase in output can be attained only by increasing costs. An approximation to the situation can be made by assuming that each producer's total costs are representable by a quadratic function of output with positive coefficients for all terms.

For given market prices, producers can maximize profits by setting marginal costs equal to the market price. Marginal costs are given by the slope of the total cost curve; if the total cost curve is quadratic, the marginal costs are given by a linear function of the quantity supplied. Under such assumptions, the quantity offered in the market by each producer is a linear function of the market price. Because control costs are composed primarily of fixed investments and the costs of labor and materials used for control (costs essentially proportional to output), the effects of controls are to shift the supply curve for each producer upward and to turn it counterclockwise. Except for departures from (or entries into) the market, the aggregate supply curve (obtained by summing over all producers) is also linear, at least near current operating levels. It also turns counterclockwise to adjust to additional controls, as shown in Figure 5-3. If no controls are imposed on foreign producers, no change occurs in the foreign aggregate supply curve. Note that the aggregate foreign supply curve may differ from the aggregate domestic supply curve. Moreover, the individual supply curves will differ among producers within both the foreign and domestic groups.

Our analysis shows that under competitive conditions of the type described, the change in price would be equal to about one-half of the average cost of controls per unit of output multiplied by the portion of consumption met domestically. At current levels of imports, the price increase would be about one-fourth of the average increase in costs per metric ton of output. This pass-on percentage implies an elastic demand function that differs greatly from the assumption by Chase Econometrics of a 90 percent overall pass-on of the costs of pollution controls.[47] Our analysis assumes that only zinc will be controlled whereas their analysis considers the micro-economic effects of the entire antipollution package. Table 4-2 gives an estimate of $42 per metric ton for the annualized cost of zinc controls. A one-fourth pass-on would consequently be about $11 per metric ton.

Table 5-1 provides some rough estimates of the effects of controls on economic aggregates of interest based on assumed supply and demand elasticities, both arbitrarily set at 1.50 for current production and consumption levels. To indicate the sensitivity of the estimates presented to variations in the elasticities, error margins are also presented in Table 5-1, showing the effects of using elasticities of 1.0 or 2.0 instead of 1.5 and allowing for an uncertainty of about 30 percent in the estimate of control costs.

The data in Table 5-1 are actually based on 1973 market data and an assumed control cost of $55 per metric ton.[48],[49] This value of $55 per metric ton has been used instead of $42 per metric ton because the lower estimate was derived from a 1971 report and presumably reflects 1970 or earlier costs structures. The allowance made for inflation over the

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[47] Chase Econometrics Association, Inc., The Economic Impact of Pollution, Bala Cynwynd, PA (March 1975).

[48] Survey of Current Business, March 1975, and prior issues for data on zinc prices, production, consumption; Bureau of Economic Analysis, U.S. Dept. of Commerce.

[49] Commodity Yearbook (1973).

Table 5-1

EFFECTS OF POLLUTION CONTROL COSTS ON THE U.S. ZINC INDUSTRY

Item	Current Amounts (1973)	Effects	Uncertainty Limits on Effects
1. Volume of domestic zinc production (thousand metric tons per year)	523	-61	-45 to -83
2. Volume of foreign zinc imports (thousand metric tons per year)	455	+46	35 to 59
3. Value of domestic zinc production (million dollars per year)	243	-21	- 9 to -33
4. Value of zinc imports (million dollars per year)	211	+28	20 to 36
5. Domestic zinc profits (million dollars per year)	Not avail.	-20	-15 to -28
6. Foreign profits from imports to the U.S. (million dollars per year)	Not avail.	+ 6	4 to 11
7. Consumer surplus (million dollars per year)	303	-14	- 8 to -24
8. Zinc price (dollars per metric ton)	464	+14	8 to 25

Notes: Calculations are based on the assumption that 1.5 is the elasticity of demand and also of supply, whether foreign or domestic. These uniform elasticities result in a price increase of one-half the fraction of consumption supplied domestically times the control costs of $55 per metric ton; i.e., the price change is (.5) (.53) ($55) x $14.6. Error terms reflect the effects of changing the elasticities from 1.5 to 1.0 or 2.0 and other uncertainties including those in the initial estimates of control costs and in updating them to 1973. Note that the estimate of consumer surplus is subject to an error of about 40 percent because of the uncertainty in the demand elasticity.

Source: Derived by SRI based on quadratic cost model developed for this project and on references cited in the text.

period 1970 to 1973 could be in error because of uncertainties in price indexes, weights, and the exact date to which the initial estimate applies. The total uncertainty in the $55 figure for 1973 is believed to be about 30 percent (i.e., about 10 percent greater than the 20 percent cited in Chapter 4). Projections to later years would require application of more recent data on inflation and could introduce further uncertainties.

Although the published data and the quadratic cost model used in this analysis did not provide estimates of current profit levels, they did permit estimates of the changes in both foreign and domestic profits as shown in Table 5-1.

Offsetting the zinc losses to some extent, measures to control cadmium (and other airborne pollutants) in zinc smelters would yield an increase of about 20 percent in the amount of by-product cadmium generated. At the current price for cadmium and the current rate of production of domestic zinc, this gain would be approximately $4 million worth of cadmium per year (450 metric tons) or about 20 percent of the projected loss in value of zinc production.

Employment Effects of Zinc Smelter Controls

Employment effects can be estimated by (1) associating with the loss of domestic zinc production a proportionate loss of employment, (2) associating with the costs of using and maintaining control equipment a proportionate gain in employment, and (3) associating with the increased sales of control equipment a proportionate gain in employment.

In 1971[59] the primary zinc industry (SIC Code 3333) was estimated to have a total employment of 7,100 (5,800 counting production workers only) and a total wage bill of 61.6 million ($47.4 million for production workers) yielding an average wage of $8,700 ($8,150 for production workers). From wages and employment reported in the 1972 annual report of the St. Joe Minerals Corporation,[11] average wage rates can be approximated as $12,000 per year. At this average wage, for the total zinc industry, wage bills in 1973 would have been $85 million. We have used $10,000 average wage as an intermediate estimate.

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[59] Annual Survey of Manufactures, Census Bureau, U.S. Dept. of Commerce (1972).

If controls had been imposed, we can infer from Table 5-1 that domestic zinc production would have decreased by about 61,000 metric tons, or about 12 percent, and its value would have decreased by $21 million or about 9 percent. Using 10 percent as an average to express effects on employment would amount to decreases of 700 workers and $7 million in wage bills.

The annual labor costs for control maintenance as given in Table 4-4 for a 100,000 metric ton per year smelter is $79,000, corresponding to an employment of about 9 persons at smelter wage rates. Annual (1973) production of 523 thousand metric tons would require about five times this total employment or perhaps 50 persons. Total investment costs in obtaining and installing control equipment would amount to $45 million for the industry and generate about $30 million in one-time wages, corresponding to employment of the order of 3,000 man-years over the period during which the new equipment would be produced and installed.

Other elements of annualized scrubber costs include $4.3 million in extra power consumption, $9.3 million worth of limestone, and $2.4 million worth of water. Depreciation and maintenance account for over $4 million per year, which could provide some additional employment either at the smelters or more probably at equipment manufacturers. If these efforts are added to those for original equipment fabrication (averaged over an assumed 15-year life), possible employment of 300 persons would be involved. In general these sources of increased employment would be small in comparison with the direct reduction of zinc industry employment. However, as calculated by Chase Econometrics,[47] if controls were introduced rapidly over a three or four year period, overall employment would increase slightly due to expansion of the pollution control industry and then decline below previous levels as primary production declines.

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[11] 1971 and 1972 Annual Reports, St. Joe Minerals Corporation, 250 Park Avenue, New York, N.Y. 10017.

The primary long-run regional effect of the various shifts in employment that are likely to arise is the net reduction of employment in the zinc industry in its areas of concentration where the opportunities for employment in other activities are relatively limited.

Finally, the monitoring and enforcement costs described in Chapter 4 could be estimated to reach from $4.20 to $5.50 per metric ton, or from $22 to $29 million per year. They would create from 200 to 300 jobs for monitoring and controlling compliance, presumably including on-site inspections and production of appropriate monitoring equipment.

Overall Effects of Zinc Smelter Controls

Table 5-2 collects the economic impact data and provides estimates of the total dollar impact of controls on zinc smelters. Data are either taken from Table 5-1 or from estimates of unemployment effects given above. The $7 million reduction in consumer purchasing power is caused by the $7 million extra paid for zinc in other products (the net result of $28 million increase in imports less a $21 million reduction in domestic production). That $7 million is added to another $7 million loss of consumer satisfaction from reduced zinc content of consumer products to obtain the total $14 million loss of consumer surplus shown in Table 5-1.

In these rough calculations it has been assumed that wages average $10,000 per year per full time equivalent employee and that unemployment is augmented by a multiplier of 2 locally. Because of local multiplier effects, national wage effects might be geographically distributed as a loss of $14 million in the vicinity of the smelters and a gain of $4 million near the producers of control equipment. The total loss in value of production is roughly equal to the change in GNP because it includes value added from zinc, cadmium, and control equipment as well as value added from production of materials used in such production.

We assume that control equipment is phased in gradually over the 15-year life of such equipment so that initial installations and replacements constitute a stable annual demand for manufacture of control equipment. There is the tacit assumption that no other environmental controls are introduced elsewhere to further perturb the economy. Taxes may be divided approximately as $3 million lost near smelters and $7 million elsewhere in the country, largely as a reduction of federal corporate profit taxes. The change in investment funds represents gross profits after taxes and thus includes capital consumption or depreciation allowances and dividend distributions.

The most significant measure of the overall effect on the national economy is the $21 million per year net reduction in GNP. The most significant local effects in smelter areas are the increases in unemployment. Other employment effects are distributed nationally. A secondary effect is the reduction of the tax base near the smelters.

The population living in smelter areas with cadmium air concentrations above one nanogram per cubic meter is seen from Figure 6-2 (in Chapter 6) to be about 2 million (assuming 100 people/km^2). Thus, of the nationally dispersed effects such as changes in federal taxes and consumer surpluses, only about one percent will be allocated to the cadmium production areas themselves. All such local allocations of nationally dispersed effects shown in Table 5-2 are below a million dollars per year and can be neglected.

Cadmium Emissions and Municipal Incinerators

As noted in Chapter 4, the controls applicable to municipal incinerators would have other antipollution values but would affect only a small portion of nationwide cadmium emissions from incineration of solid wastes. The cost of controls would normally fall on the local population either as increased charges for refuse collection and disposal or as increased local tax rates (unless, as recently in the case of municipal water treatment, massive aid were provided by state or federal governments). Although considerations of equity might suggest that these costs be recovered by increasing refuse service charges, or basing such charges on weight or volume of solid wastes collected, the record-keeping problems of such procedures would be so great that most municipalities would probably prefer to use tax revenues or increased service charges. In any case, the total costs would be absorbed by the total population. The only non-health economic benefits involved would be the gain to the producers of requisite control equipment or to those local persons who maintain or monitor it.

The model incinerator cited in Table 4-3 has a capacity for 263 metric tons per day or 0.096 million metric tons per year, and an annualized cost of $110,000. Total costs for 193 public incinerators would be about $22 million per year plus another $2 million for monitoring and control. Somewhat more detailed analysis using both the cumulative distribution of incinerator capacities given in Figure 4-1 and the estimates of annualized costs given in Table 4-3 yields an estimate of $132,000 of annualized costs or $25.5 million per year for

Table 5-2

CHANGES IN ECONOMIC BENEFITS CAUSED BY ADDING ZINC SMELTER CONTROLS

Economic Aggregate	Change Induced by Pollution Control (Million Dollars Per Year)	
	Smelter Locality	National
Effects on Wages		
Zinc and cadmium	- 7	- 7
Control equipment manufacture	0	+ 2
Local services (multiplier effect)	- 7	- 5
Total Wages	-14	-10
Effects on Value of Production		
Zinc	-21	-21
Cadmium	+ 4	+ 4
Control Equipment	0	+ 3
Consumer purchasing power (consumer surplus)	0	- 7
Total Production	-17	-21
Effect on Domestic Profits		
Zinc	-20	-20
Cadmium	+ 2	+ 2
Control equipment	0	+ 1
Profit portion of consumer purchasing power	0	- 2
Total Profits	-18	-19
Effect on Taxes	- 3	-10
Effects on Investment Funds	NA	- 9
Effects on Balance of Trade	NA	-28

Source: Derived by SRI from data in Chapter 5. Investment costs are assumed to be averaged over the life of the investment.

the whole country plus $2.5 million for monitoring and enforcement. Using the 20-percent uncertainty limit results in an estimate of annualized costs nationally of from $21 to $31 million plus $2 to $3 million for monitoring and enforcement. We assume these costs are borne by the localities involved, except for a portion of the monitoring and enforcement costs.

Asbestos Controls

The impact of asbestos controls can be assumed to be almost entirely on consumer surplus. This impact will be distributed over all users of asbestos products. In the first place, direct sales of asbestos products to final demand are small (perhaps one-sixth of the total). In the second place, asbestos products are largely free of competitive products. Indirect demands for asbestos in the hundreds of places where it is fabricated into products of other industries provide an aggregate demand that should be highly inelastic. Control costs are thus likely to be passed on fully as minor increases in the costs of the various consumer products that contain asbestos. Although these price increases for asbestos products may be somewhat augmented by application of markups in the consumer products (e.g., there may be a small multiplier effect), the asbestos content is generally small enough to preclude any significant reduction in demand for the various products incorporating some asbestos.

Asbestos Production Controls

Control costs, as summarized in Chapter 4, appear to be very small as a percentage of the value of the asbestos products themselves, and an extremely small fraction of the value of the end-items using asbestos. Effects on the demand for the wide distribution of products can be assumed to be inconsequential, and the primary impact would be on consumer surplus for asbestos sales. The net effect would then be a reduction in aggregate consumer surplus for the whole economy about equal to the cost of controls. The costs of controls vary somewhat over various asbestos items, ranging from 0.1 percent of the costs of friction materials to 5 percent of the cost of asbestos textiles. Asbestos textiles account for only about 3 percent of the total asbestos market, however, so the overall cost of controls will amount to only a fraction of one percent of the total value of asbestos production.

Total annualized costs have been estimated here to be about $2.9 million per year including enforcement costs with an estimated range of ±20 percent. The total imputed effects on consumer surplus are estimated to be a reduction falling in the range from $2.4 to $3.5 million per year. Offsetting social gains would arise in the form of perhaps from 150 to 250 jobs per year associated with the production of control equipment, its use and maintenance, and in control and enforcement.

Elimination of Asbestos Brake Linings

The elimination of asbestos from automobile brake linings as discussed in Chapter 4 is admittedly hypothetical in the absence of any substitute material of demonstrated feasibility. Under the assumptions, however, including a cost of 50 percent over present linings, the immediate effects are estimated to be:

- $13.8 million per year in increased costs of brakes for new cars.
- $50 million per year in increased costs of replacement brakes.
- A loss of raw asbestos sales of $14.8 million dollars per year.
- Enforcement costs of $1.5 million per year.
- Total substitute brake costs of $191 million per year, including $22 million for the substitute material.

- A minor loss in automobile sales per year of possibly $15 million (corresponding to a reduction in new car sales of perhaps 5 thousand vehicles as calculated by a special elasticity-of-demand study for this project).
- An imputed or welfare loss of about $65 million per year in consumer surplus for automobile owners.
- An increase in employment in the industry producing the substitute material, augmented by increased employment in enforcement forces but offset by a reduction of employment in the asbestos industry. A substantial net increase in employment would be expected, largely in the production and installation of the substitute linings. With the material unspecified and the economic structure of its industry unknown, the employment involved in producing the material and in brake relining cannot be estimated reliably but might amount to 10,000 jobs per year, less about 6,000 jobs currently in making, installing, and replacing asbestos linings.

Aside from the employment effects and any allowance for the uncertainty in finding a feasible substitute for asbestos linings, these estimates are all subject to a log-normal two-sigma error of at least 25 percent. For example, the net increase in jobs of about 4,000 should be regarded as lying in the range from 3,200 to 5,000.

The dominant negative local impact of these changes would be the loss of 150 jobs in areas of asbestos brake producers. With a multiplier effect doubling the cost of each job loss, these local impacts might total $3 million per year with confidence limits of $2.4 million to $3.8 million annually. The major national impacts would be the consumer surplus loss of $65 million per year (confidence limits $52 million to $81 million per year).

Chapter 6

EXPOSURE TO HAZARDOUS WASTES

Background

Few exposure models of the type needed for this analysis have been attempted in the past because results that are accurate at the local level require detailed information on such parameters as the micro-meteorology of the area, the physical and chemical characteristics of each emission, the quality of ground water supplies, and the composition of the soil. Studies that have related the amounts of emitted contaminants to the extent of the resultant exposures have generally been too complex to be applied to a general model (e.g., the aerial dispersion models used in the Purdue Cadmium Project[2-1] and in the AEC manual, "Meteorology and Atomic Energy,"[6-1] are dependent on variables for which data are generally not available).

Because no adequate prior models were discovered in the literature search for this project, we had to develop our own composite model to convert emission rates into contaminant concentrations in the air, water, soil, food, and so forth to which people are exposed. Although portions of the model are based upon earlier models used for radiological and other environmental contamination analyses, the overall model represents a first attempt to define exposure conditions in a manner that can be conveniently integrated into other portions of the analysis.

[6-1] D. H. Slade, editor, "Meteorology and Atomic Energy," U.S. AEC Technical Information Center, Oak Ridge, Tenn. (July 1968).

The objective of this part of the study is to define a general model of exposures to contaminant materials that will relate the rates of emission by a source to the contamination levels that will be created in the areas around it. The model should be flexible enough to deal with a single emission source on the one hand and with areawide or even nationwide contamination levels on the other. To handle the greatest variety of input data and analytical results, it should be compatible with a wide range of detail for such factors as wind patterns, type of contaminants, source height and heat, population distributions, and surrounding operational activities. At the same time, its output data must be in a form that can be applied to the human hazard model in the succeeding part of the analysis.

The scope of the model need only cover the contaminants that are of concern (e.g., cadmium or asbestos), but modifications of the basic model should be applicable to many different contaminants. Media exposed should include air, water, and land surface, as well as others that may be significant in the case of individual contaminants, such as food, tobacco, and clothing.

Method of Analysis

Different methods of analysis are required for each of the media. In general, the logic of the analysis progresses in the following steps:

(1) Convert the rate of air emissions from the source into levels of contaminant concentrations at points around the source. This provides a measure of exposure for inhalation.

(2) Convert the air concentrations to rates of deposition onto the earth's surface.

(3) Convert deposition rates to concentrations in biologically active portions of the ground and the water supply. In the case of sources emitting contaminants directly to the ground or to water, the analyses will start with this step.

(4) Convert the exposures from air, ground, and water concentrations to an estimate of contamination of foods grown in the area.

(5) Sum the exposures from cadmium in air, ground, water supplies, food, and other media into an equivalent total exposure to human beings in the area of interest.

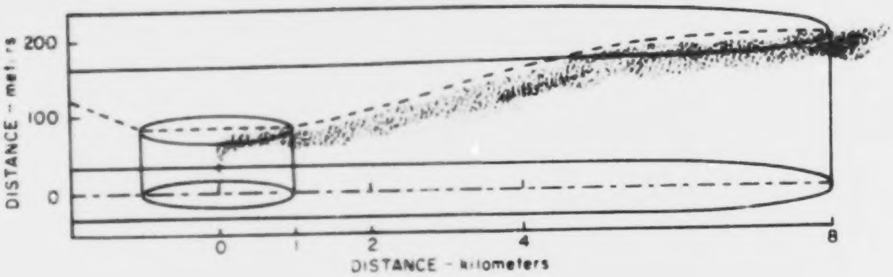
These steps have been followed in building the following simplified models for air, ground, water, and food exposures.

Air

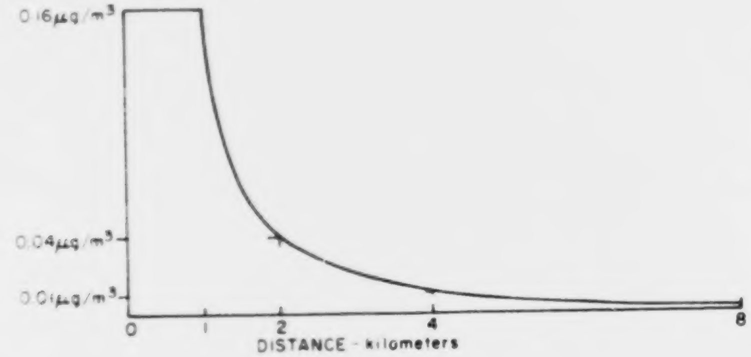
To estimate air exposures from any emission source, assume that the source is continuously emitting a flow of contaminants at a rate of Q' g/sec into the airstream. This flow will become diffused through the lower layers of the airstream with an "expected concentration C" equal to its average concentration at some distance r in the downstream air times the probability that any given point at that distance will be in the airstream. For equal frequencies of all wind directions, this expected concentration level will be the same for all equidistant points surrounding the source.

Because the circumference of the concentric circles surrounding the source is proportional to the distance r, the contaminant will be dispersed in propostion to 1/r just through the effects of diffusion around the source. (As explained below, the close-in limit of this model is assumed to be 1 km.) In addition, air diffusion theories indicate that contaminants will disperse vertically in a "mixing layer" that is proportional in depth to $\sqrt[3]{r}$ (see Ref. 52, p. 197, Figure 5.2). If we assume that the mixing layer is 100 m high out to a distance of 1 km from the source, that it rises in proportion to $\sqrt[3]{r}$ at further distances, and that over a long period the contaminant will disperse equally in all directions, then the layer will appear as illustrated in Figure 6-1(a).

A) HEIGHT OF CONTAMINANT "MIXING LAYER" IN THE AIR


200
100
0
DISTANCE - meters
0
1
2
4
8
DISTANCE - kilometers

B) CONCENTRATION OF CONTAMINANT IN MIXING LAYER
(FOR EMISSION RATE OF 1g/sec)



C) DEPOSITION RATE OF CONTAMINANT ONTO GROUND

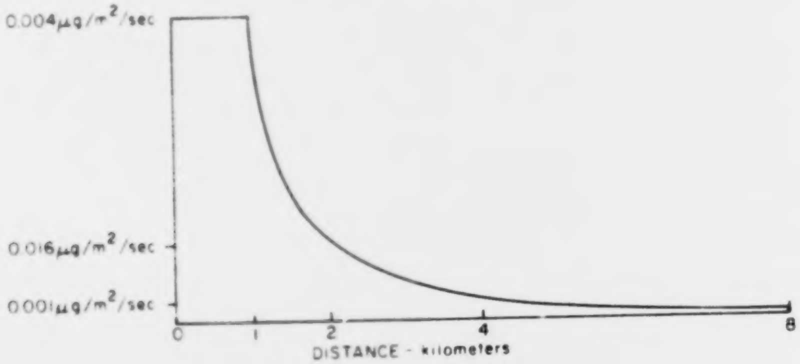


FIGURE 6-1 MODEL OF CONTAMINANT DISTRIBUTION AROUND AN EMITTING SOURCE (Wind Frequency Equal in All Directions)

If we further assume that the average wind speed is 10 m/sec, then from geometric considerations, the expected air concentration (neglecting deposition) at radial distances greater than 1000 m will be:

$$C \ \mathrm{g/m^3} = \frac{Q' \ \mathrm{g/sec}}{10 \mathrm{m/sec} \cdot 10 r^{1/3} \mathrm{m} \cdot 2\pi r \ \mathrm{m}} \qquad (6\text{-}1)$$

$$= \frac{Q'}{2\pi \cdot 100 r^{4/3}} \ \mathrm{g/m^3} \quad .$$

C is the contaminant air concentration within the mixing layer at distance r and Q' is the contaminant emission rate from a continuous source;

10/sec is the average wind speed in meters per second

$10r^{1/3}$ is the depth of the mixing layer in meters

r is the distance from the contaminating source, in meters.

But in addition to dispersion, the air concentrations will decline by deposition of contaminants onto the ground surface. This deposition rate is often approximated by a "deposition velocity v_d" (Ref. 52, p. 204). For a given wind speed and no lateral dispersion of the contaminants, the deposition velocity will reduce concentrations exponentially with distance. However, if integrated averages of deposition under all wind speeds are taken, the value of residual air concentrations will more nearly resemble a power function. Such a relation, where C is proportional to $1/r^2$, has been experimentally observed by Slade (Ref. 52, Figures 4.24 and 4.40). For simplicity, this function will be taken here, providing a value of expected air concentration that is proportional to $1/r^2$.

Concentrations near the surface at distances very close to the source are less than expected under the $1/r^2$ assumption because most sources emit from some height (such as a stack) and it takes time for the concentrations to descend to ground level. For example, both surface air concentrations and ground deposition rates (which are closely proportional to surface air concentrations) seem to peak at some distance up to about 1 km from industrial emitters (see Ref. 52, Figures 4.2 and 4.4).

The model combining deposition and diffusion effects assumes that the total contaminants suspended in the air remain constant out to a distance of 1 km, and then decline in proportion to $r^{-2/3}$, due to deposition. This function is shown in Figure 6-1(b). The concentration equations, as modified to show deposition as well as dispersion (for Q' in g/sec and r in m), are:

$$C\ \mathrm{g/m^3} = \frac{Q'}{2\pi \cdot 100r^{4/3}} \cdot \frac{100}{r^{2/3}} = \frac{Q'}{2\pi r^2} \qquad (6\text{-}2)$$

$$= \frac{Q'}{2\pi \cdot 10^6} \quad \text{for } r < 1000 \text{ m} \qquad (6\text{-}2a)$$

$$= \frac{Q'}{2\pi r^2} \quad \text{for } r \geq 1000 \text{ m} \quad . \qquad (6\text{-}2b)$$

These concentrations are additive from each source and from natural background. Confidence intervals ($\pm 2\sigma$) are likely to be quite wide for the model relative to any given contaminant and any downwind location, because of both micro-meteorological variations and generalizations involved in the model. By analogy to experience with models for nuclear fallout, we estimate that the confidence limits for any one source will be of the order of ± a factor of 10.

Ground

Deposition rates from air concentrations can be related to air concentrations through the deposition velocity v_d mentioned above. The "deposition rate per unit area d'" is:

$$d'\ \mathrm{g/m^2/sec} = v_d\ \mathrm{m/sec} \cdot C\ \mathrm{g/m^3} \quad . \qquad (6\text{-}3)$$

The "total deposition rate D'" is the integral of the area deposition rates over the entire surface of the earth. In simplified form, the earth's surface ($5 \cdot 10^8$ km^2) can be expressed as a plane circle of radius 8,900 km if we assume that D' varies as a function of the distance from the emitter. Therefore, total deposition rate can be approximated by an integral of the form:

$$D' \text{g/sec} = \int_{r=0}^{8.9\times10^6 \text{m}} d' 2\pi r dr = 2\pi v_d \int_{r=0}^{8.9\cdot10^6} c\ r dr$$

$$= 2\pi v_d \left\{ \int_{r=0}^{1000} \frac{Q' r dr}{2\pi \cdot 10^6} + \int_{r=1000}^{8.9\cdot10^6} \frac{Q' r dr}{2\pi r^2} \right\} \qquad (6\text{-}4)$$

$$= v_d Q' \left\{ \frac{r^2}{2 \cdot 10^6} \Big|_0^{1000} + \ln r \Big|_{1000}^{8.9\times10^6} \right\}$$

$$= v_d Q' [0.5 - 0 + 15.9 - 6.9] = 9.5\ v_d Q' \approx 10\ v_d Q' \ .$$

An approximate value for deposition rate per unit area as a function of air concentration can be derived by combining the above two equations and introducing the equality $D' = Q'$. (By the preservation of mass principle, the total deposition rate D' will equal the emission rate Q' under equilibrium conditions.)

$$d' \text{ g/m}^2\text{/sec} = v_d \cdot C = \frac{D'}{10Q'} \cdot C = \frac{C}{10} \ . \qquad (6\text{-}5)$$

Expected values for deposition rates are illustrated in Figure 6-1(c). Thus, long-term deposition rates in g/m^2/sec will average about one-tenth the long-term expected air concentrations in g/m^3. The level of uncertainty of this estimate, however, is even greater than for air concentrations, largely because of micro-meteorological variations in deposition rates but also because of particle size variations and approximations in the model. For these reasons, the estimated uncertainty levels in point-to-point ground deposition are as much as a factor of 30.

Average deposition rates over a large area will also be about 10 times smaller than average air concentrations. Variations of the averages will be somewhat larger than the variations in average air concentrations: about a factor of 10.

Buildup of contaminants in soils could continue indefinitely except as counteracted by natural fixation and depletion processes. Since these processes are not known from existing data, estimates must be based on comparison with analogous contaminants. The usual model for turnover of organic and other foreign matter in the soil is

$$\frac{dx}{dt} = A - Lx \quad .$$

where x is the amount of matter present initially

A is the annual input

L is the fraction removed each year.

For equilibrium conditions after air depositions to the soil have continued for many years, the input will be balanced by depletion so that

$$\frac{dx}{dt} = 0 \text{ and}$$

$$x_e = \frac{A}{L} \quad ,$$

where x_e is the amount of matter present in equilibrium conditions.

Water

Contaminant concentrations in water depend more than air or soil concentrations on local factors, because water is influenced by upstream sources, subsurface contaminants, and direct discharges as well as by air deposition. Unfortunately, we do not know of any large-scale water flow model that can be applied to the water concentration problem. However, as a gross rule of thumb, one may conclude that water concentrations will be correlated with (1) air concentrations, and (2) soil concentrations of the contaminant of concern. The argument for correlation with air contaminants is the fact that most municipal water supplies are taken from surface waters that are susceptible to deposition of airborne contaminants. The argument for correlation with soil contaminants is the obvious propensity of flowing waters to take any contaminants that they come in contact with into solution or suspension. Furthermore, each argument can be adduced in partial support of the other because of the close association between air and soil concentrations that has been described above. Since we work primarily in the study with air concentrations, the basis for analyzing water concentrations will be:

$$\frac{\text{water concentration in } \mu\text{g/l}}{\text{background water concentration}} = \frac{\text{local air concentration in } \mu\text{g/m}^3}{\text{background air concentration}} .$$

Food

Because of discrimination procedures by plants and animals against excessive levels of any mineral, increases in soil concentrations of contaminants are not proportionately reflected in higher food concentrations. The increases in food concentrations are roughly proportional to the square root of the increased soil concentration.[53,54] However, most food comes from locations that are distant from the consumer. Brown and Pilz[55]

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[53] L. Friberg et al., "Cadmium in the Environment," Table 3.3, CRC Press, Inc., Cleveland, Ohio (1974).

[54] A. L. Page and F. T. Bingham, "Cadmium Residues in the Environment," Residue Review, Vol. 48, p. 26 (1973).

[55] S. L. Brown and U. F. Pilz, "U.S. Agriculture: Potential Vulnerabilities," Stanford Research Institute, Menlo Park, Calif., p. 63 (January 1969).

have calculated that while food sources vary in proximity to consumers, the average movement of unprocessed food in the United States is at least 650 miles from producer to processor, and that the movement of processed food from processor to consumer is another 400 miles or more. The average area over which soil concentrations should be calculated to determine food cadmium levels, then, extends to a radius in the order of 1,000 km around each consumer. The impact of cadmium emissions on food is accordingly taken to be regional rather than local in nature. (Other evidence derived by Capener for this study shows that concentrations of cadmium in food are correlated with the sizes of cities sampled, which contradicts this assumption. Locally procured fresh foods such as milk may explain the correlation, but development of a plausible cause-effect model must await future studies.)

Illustrative Application: Cadmium

Although the cadmium flow chart in an earlier chapter shows that almost three-quarters of the cadmium emitted to the environment ends in land disposal, the major sources of exposure to humans are ingestion from food and water and inhalation from the air. The models necessary to derive these exposures are developed below from the general exposure models.

Air

Maximum levels of cadmium measured during a year's period in air exhibit a mean of approximately 0.003 $\mu g/m^3$ and a 2σ range of ± a factor of 10. Maximum urban levels show a mean of 0.01 $\mu g/m^3$ with the same proportionate range, and average levels seem to be about one-third of the maximum ones (Ref. 3, p. 206). This implies that average background air levels are in the order of 0.001 $\mu g/m^3$, ± a factor of 10. The maximum monitored level in recent years at any station was 0.69 $\mu g/m^3$ in East Helena, Montana.

Increases over background levels can be calculated from the general air concentration equations given above. For example, concentrations resulting from the model zinc smelter specified in Table 4-2 can be calculated from equations (6-2a) and (6-2b). The calculations show that an uncontrolled cadmium emission rate of 4.1 g/sec will create a maximum air concentration of 0.65×10^{-6} g/m^3. But the concentration will be higher than the basic model indicates because some portion of cadmium already deposited will be resuspended and recirculated. Experiments done by Purdue University[56] suggest that 20 to 30 percent of measured concentrations are due to resuspended particles. An average of 25 percent would imply that measured concentrations will be 100% ÷ 75% = 133% of the values calculated above, or 0.87×10^{-6} g/m^3 out to a distance of 1 km from the smelter. This maximum concentration will encompass a circular area of 3.14 km^2, and concentrations at further distances will be inversely proportional to the area covered.

If we multiply the areas affected by 8 to consider all U.S. smelters, then we can derive the coverage estimates shown in Figure 6-2. We can estimate the population covered by assuming an average density of 100 people per km^2 (slightly less than the average density in Pennsylvania). The resultant values incorporate assumptions that concentrations from the eight model smelters will equal those from the sum of the actual U.S. zinc smelters listed in Table 4-1, and that overlaps between their contamination areas are negligible.

Similar calculations can be made for cadmium air concentrations around municipal incinerators. The model uncontrolled incinerator described in Table 4-3(a) emits 1.1×10^{-3} g/sec of cadmium and creates a

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[56] K. L. Yost et al., "The Environmental Flow of Cadmium and Other Trace Metals," Progress Report, prepared by Purdue Univ., p. 95 (1974).

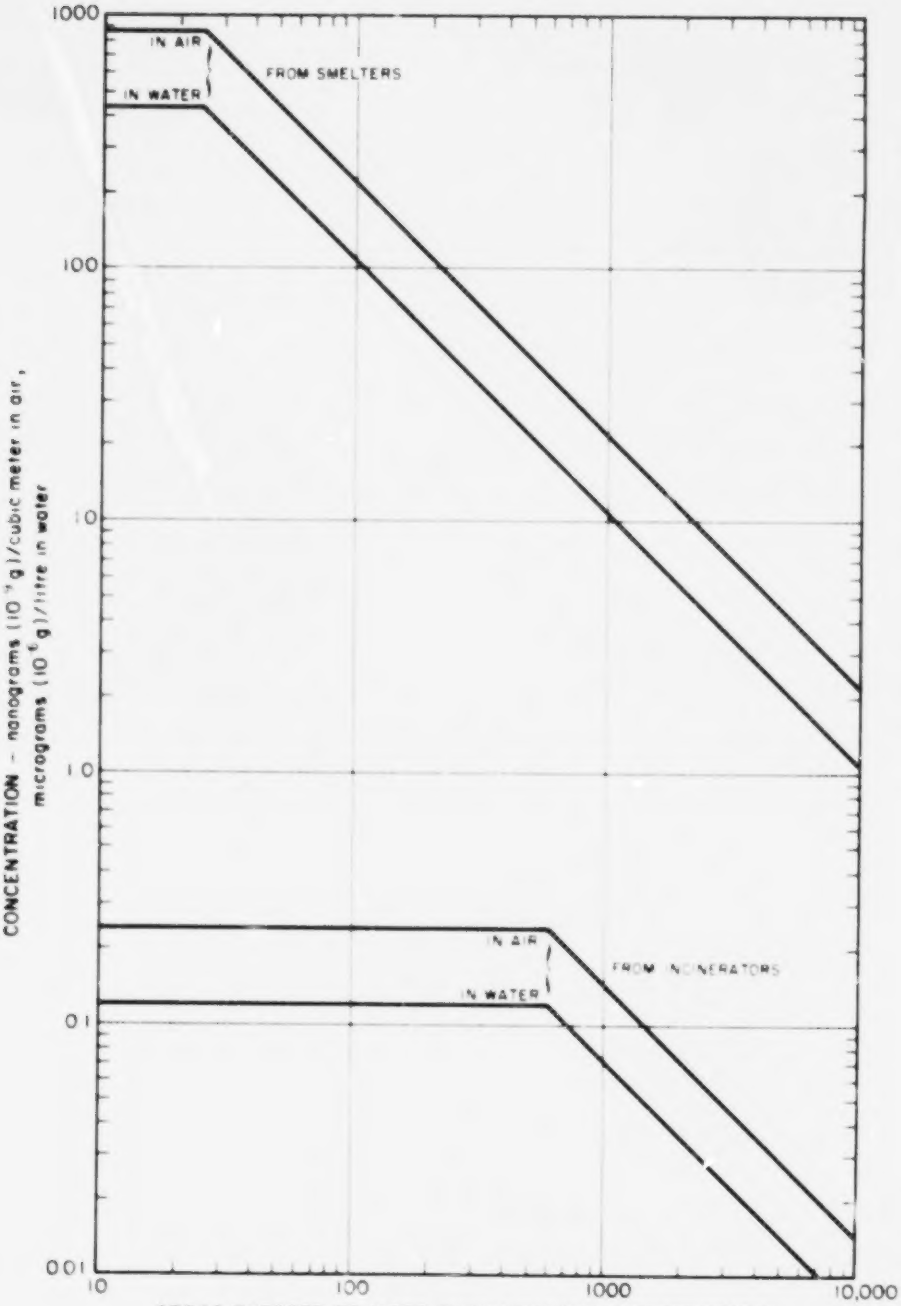

FIGURE 6-2 CADMIUM AIR AND WATER CONCENTRATIONS FROM U.S. ZINC SMELTER AND MUNICIPAL INCINERATOR EMISSIONS (UNCONTROLLED)

concentration of 0.24×10^{-9} g/m^3 within a radius of 1 km. For 193 municipal incinerators of the same size, the total area covered with this concentration will be 600 km^2. Population densities around municipal incinerators (mostly in the Northeast) can be taken as 200/km^2--about the same as the average for the Northeast states.

Controls will reduce the air concentrations in proportion to the reduction in emissions. Smelter controls are expected to eliminate 0.95 of the emitted levels, with a two-sigma confidence band lying between 0.905 and 0.998. Incinerator controls will eliminate an expected 0.85 of emissions, with confidence limits of 0.74 and 0.98.

Ground

Total ground levels of cadmium concentration for uncontaminated soils amount to a mean of 0.06 ppm and a two-sigma range of a factor of 10 (Ref. 3, Table IV-1). (This compares with a mean value in the whole earth's crust of 0.15 ppm.) Assuming that the biologically active soil zone is the top 10 cm (Ref. 3, p. 279) and that soil weight averages 1 g/cm^3, then this concentration of 0.06 ppm is equivalent to:

$$0.06 \cdot 10^{-6} \times 10 \text{ g/cm}^2 \times 100^2 \text{ cm}^2/\text{m}^2 = 6 \times 10^{-3} \text{ g/m}^2 \quad \text{a factor of } 10 \ .$$

Deposition rates will of course be additive to this normal ground concentration. Addition of phosphate fertilizers to the soil can increase cadmium concentrations by a factor of 10 or more (see Schroeder as reported in Fulkerson, Ref. 3, p. 73). Concentrations of as much as 30 ppm have been observed in soils around a zinc smelter (Ref. 3, p. 279).

Removal of cadmium from the biosphere in the soil is very difficult to estimate. Removal rates for mercury from sediments in water are estimated at about 15 percent to 50 percent per year (ref. personal communication, Buford Holt, SRI). For carbon in soil, the removal rates are about 5 percent to 10 percent per year.[57] Removal rates for cadmium can be expected to be much slower, and will be estimated here to be 2 percent per year, a factor of 3. This estimate is consistent with observed residual concentrations near steel mills in Gary, Indiana (personal communication, Dr. Jack Yost, Purdue University Cadmium Project). Therefore, for cadmium, the long-term buildup or decline in cadmium levels caused by a specific change ΔA in the annual emission rate A is:

$$\Delta x_e = \frac{\Delta A}{0.02} = 50 \Delta A \quad .$$

This level, however, will not be approached until about a century of emissions at the stable rate. Changed levels in the first year will approximate the derivative function:

$$\Delta x = \Delta A - 0.02 x_o \quad .$$

Water

The mean level of cadmium in uncontaminated headstream waters is roughly 1 μg/liter; that is, 1 ppb, with a two-sigma confidence factor of about × 10. The U.S. Public Health Service drinking water standard is at the upper end of this range: 10 ppb. Contaminated streams have been observed with as much as 130 ppb (Ref. 3, p. 218).

The water concentration model that will be used for cadmium is the one correlated with air concentration, i.e.:

$$\text{water concentration (in g/l)} = (1/2 \cdot 10^3) \text{ air concentration (in g/m}^3) \quad .$$

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[57] W. A. Reiners, "Terrestrial Detritus and the Carbon Cycle," in Carbon and the Biosphere, G. M. Woodwell and E. V. Pecan, editors, USAEC (August 1973).

Supportive evidence for this model can be found from a U.S. Geological Survey finding that, as in air, "higher concentrations of cadmium in water generally occur in areas of high population density" (Ref. 3, p. 218). Also, both the confidence intervals (a factor of 10) and the extreme values (230 times background for air and 130 times background for water) are of the same orders of magnitude as the model would indicate.

Effects of emission controls on water concentrations can be calculated easily from the above formula, since any changes due to controls will be one-half the magnitude (measured in ng/l) of the changes (measured in ug/m^3) estimated in air. The comparable curves are illustrated in Figure 6-2.

Food

"Normal" food concentrations of cadmium are reported by Friberg to be about 0.05 ppm (Ref. 54, p. 25). Schroeder reports a normal value of 0.35 ppm, but this value is considered too high by other investigators. Nevertheless, a confidence limit on these estimates of ± a factor of 10 (i.e., lying in a range between 0.005 and 0.5 ppm) seems reasonable.

Other measured concentrations in four foods indicate values ranging from 0.0015 to 0.07 ppm (Ref. 54, p. 30). This would imply a mean food level of perhaps 0.01 ppm and two-sigma values of ± a factor of 10. The estimate relevant to this analysis--integrated total foods eaten by individuals over a time period of 1 to 50 years--will have much lower variance. For that figure, an estimate of 0.01 ppm ± factor of 3 can be used. However, we will not consider variability of food concentrations in this analysis.

Illustrative Application: Asbestos

Chapter 7 will document the hazards of asbestos, which are primarily from inhalation of airborne particles. Therefore, air concentrations are the major exposure routes of concern for asbestos. Where asbestos is emitted into the air from man-made sources, we will adopt the same air transport model that has been used for cadmium.

Available data[3] indicate that urban levels, averaging about 29 ng/m^3, are very much higher than nonurban concentrations, which generally appear to be less than 1 ng/m^3. Much of these urban concentrations came either from the industrial sources or the brake lining residues that are considered in this analysis, although other major sources include building construction and demolition activities.

The asbestos industry data tabulated in Table 4-4 show total emissions of 547 metric tons per year, or 17.5 g/sec. Dividing these emissions among the 659 operating asbestos plants yields an average of 0.026 g/sec from each plant. Air concentrations from Equation (6-2b) will thus reach a maximum of 4.1×10^{-9} g/m^3. Additional quantities should be included to allow for refloatation of particles deposited on the ground. Since asbestos particles tend to be smaller than cadmium particles, they should refloat more easily. We will assume that 33 percent of all asbestos particles in the air at any time have been refloated; so the corrected maximum concentrations will be $4.1 \times 10^{-9} \div (1.00 - 0.33)$ or 6.2×10^{-9} g/m^3. These concentrations will extend 1 km from each plant (covering a total area of 659 πr^2, or 2060 km^2), and fall off inversely with the square of further distances from the sources.

Asbestos contamination from brake linings presents an even more difficult estimating task because the emission sources are so diffuse. If we consider emissions from each of the 130 U.S. cities of over 100,000 population as a single source and add them to the estimated 30 plants producing friction products (i.e., brakes), the total sources can be taken as 160. This number can be divided into the 339 metric tons per year (11 g/sec) potential reduction in air emissions from eliminating asbestos brakes to obtain an average emission rate per source of 0.07 g/sec. Maximum air concentrations, corrected for the refloatation factor, will be $0.07/(2\pi \cdot 10^6) \div 0.67$, or 17×10^{-9} g/m^3, over an area of 500 km^2.

Areas covered by the calculated concentrations due to both the production of asbestos products and the use of asbestos brake linings are illustrated in Figure 6-3. Since both asbestos products and brakes are primarily associated with urban areas, the density of populations exposed can be taken as an average of 2,347 people per square kilometer, as shown above in Table 4-5. That estimate, which is based on city population densities, is more than 10 times as high as the cadmium estimates, which are based on statewide densities.

Controls imposed on asbestos industry emissions would be expected to reduce the concentrations by about 96 percent, as described in Chapter 4. Confidence limits on this value reflect uncertainties in the values of both emissions and control effectiveness. The overall limits, assuming independence of the two uncertainty factors, can be expressed as:

$$
\begin{aligned}
\text{log of uncertainty} &= \sqrt{\begin{pmatrix}\text{log of emissions}\\ \text{uncertainty}\end{pmatrix}^2 + \begin{pmatrix}\text{log of control}\\ \text{uncertainty}\end{pmatrix}^2} \\
&= \sqrt{(\log 1.31)^2 + (\log 1.03)^2} = \sqrt{0.27^2 + 0.030^2} \\
&= \sqrt{0.0729 + 0.0009} = \sqrt{0.0738} \\
&= 0.272 = \log 1.3125
\end{aligned}
$$

The uncertainty factor in reduction of industry emissions is very close to the largest individual uncertainty factor: 1.31.

Eliminating the production and use of asbestos brakes will result in 100-percent reduction of the brake-related emissions shown in Figure 6-3, again with a 1.31 uncertainty factor.

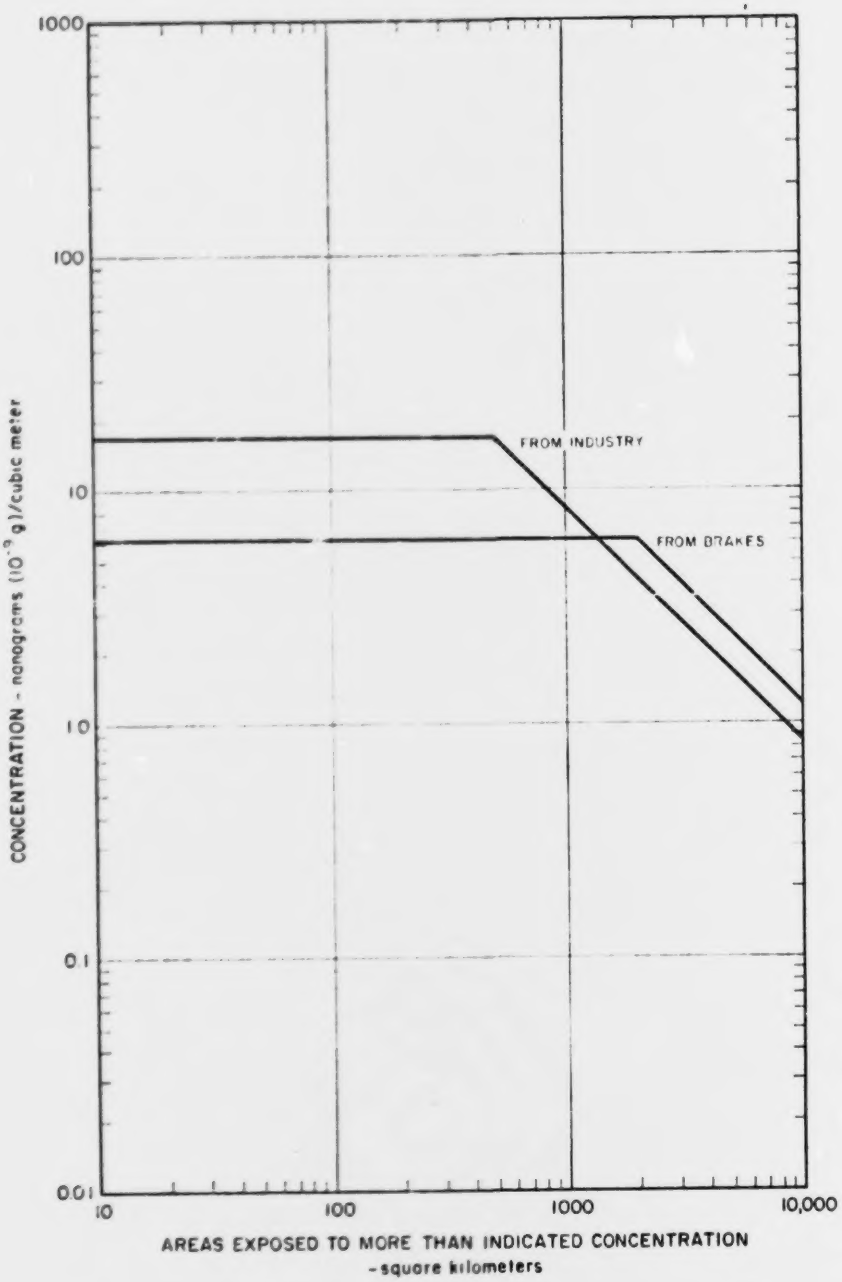

FIGURE 6-3. ASBESTOS AIR CONCENTRATIONS FROM U.S. ASBESTOS INDUSTRY AND BRAKE LININGS

Chapter 7

RISKS TO HEALTH

Introduction

This chapter describes how estimates of waste exposure levels from Chapter 6 can be combined with epidemiological data to generate estimates of health effects. One useful way of quantifying such estimates is through the use of dose-damage curves. Dose is a measure of exposure to some pollutant in our environment and damage is some health effect (e.g., mortalities) associated with the dose.

An intermediate phenomenon, absorption of the pollutant from the environment into the body also occurs. But in many, probably most, cases of interest to EPA, the processes by which such absorption takes place are not well understood, and the relationships between observed levels of pollutants and health effects are subject to considerable uncertainty. For effective decision making, a dose-damage curve must be accompanied by an indication of its reliability.

Here we express reliability by drawing confidence limits around the dose-damage curves. Dose-damage estimates of this type have been developed to:

- Provide an empirical basis for illustrating risk-benefit methodology.
- Identify areas where further data would improve the quality of the results.

The attempt to provide an empirical basis proved available data were sparse, fragmentary, too narrowly conceived, and in some cases, contradictory. But it did set forth the considerations needed for a comprehensive analysis of environmental health hazards in a manner that documents the missing as well as the available data elements as clearly as possible.

Cadmium Example

The concepts described above are first illustrated by applying them to the case of cadmium. Very little is known about the processes by which man's body extracts cadmium from his environment. Major uncertainties exist as to absorption and retention as a function of routes of intake, chemical forms of the element, and the synergistic or antagonistic effects of other components (Reference 3, Fulkerson, Chapter VI).

The best medical evidence (based on analysis of metabolic processes, systemic effects, and dose response relationships) indicates that the kidney is the critical organ in chronic cadmium poisoning. However, statistical correlation studies indicate much higher cadmium-related mortality rates from cardiovascular diseases and from cancer. For the chronic exposures that are of interest in this study (chronic exposures require stricter environmental standards than acute exposures), the significant health threats appear to be bracketed on the low side by kidney effects, and on the high side by cardiovascular and cancer effects.

Body Burden Model

Because of (1) uncertainties in the amounts and pathways of cadmium in the body, (2) the several physiological systems involved, and (3) the complicated internal cadmium redistribution that takes place among such systems, we assume a simplistic view of how cadmium builds up in the body. A certain fraction of the cadmium brought into the body by ingestion or inhalation is absorbed into the bloodstream. The fraction absorbed by ingestion is different from the fraction absorbed by inhalation. A large fraction of the cadmium in the tissues is slowly excreted at a rate that is proportional to the total amount present. There will be a slow buildup until around age 50 when the amount leached from the total body burden is the same as the amount deposited. Once this point is reached the body burden will remain constant. The assumption of no change in body burden after age 50 provides us with a convenient upper limit on burden and a cutoff on time of exposure.

To apply the above model it is necessary to know the levels of cadmium in food, water, and air that will cause equal rates of buildup in the body. The amount we use as a reference is a daily concentration of 1 $\mu g/m^3$ of cadmium in air. From the data shown in Table 7-1, we estimate that 24 hours exposure to air containing 1 $\mu g/m^3$ of cadmium is equivalent to a daily ingestion of 166 μg via food and water. (This calculation assumes that cadmium absorption via the gut is as high as via the lungs--a probable overestimate.) The multiplier for the two-sigma confidence levels around this value is about 2.0.

Actually cadmium dust concentrations of 1 $\mu g/m^3$ are much higher than average. Concentrations averaging 1 $\mu g/m^3$ or more can be found in factories where cadmium is a major part of the industrial process and no precautions are taken. According to Friberg,[58] the maximum average value reported at a U.S. nonfactory location was 0.05 $\mu g/m^3$. The value for lower Manhattan was 0.02 $\mu g/m^3$, and values for nonurban sites were 0.003 $\mu g/m^3$. Ingestion from water averages less than 2 μg/day--the equivalent of 0.01 $\mu g/m^3$ or less in air. On the other hand, the cadmium content of food in the daily American diet averages about 50 μg/day. Expressed in equivalent $\mu g/m^3$, it ranges from about 0.10 to 0.70 $\mu g/m^3$ with an average of about 0.30 $\mu g/m^3$.

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[58] L. Fiberg et al., "Cadmium in the Environment: A Toxicological and Epidemiological Appraisal," APTD-0681; PB-199-795, prepared by the Karolinska Institute, Stockholm, Sweden, for the U.S. Environmental Protection Agency, Air Pollution Control Office (April 1971).

Table 7-1

QUANTITIES USED TO ESTIMATE EQUIVALENT CADMIUM INTAKE

Quantity	Low	Mean	High	Source
Mean daily volume of air breathed (m^3)	17.5	20	23	Human Factors Handbook
Fraction available of cadmium inhaled	.10	.25	.40	Friberg et al. (Ref. 58)
Fraction available of cadmium ingested	.01	.03	.05	Friberg et al. (Ref. 58)

Tobacco, particularly that in cigarettes, contains appreciable amounts of cadmium, which on burning passes into the tobacco smoke. As a consequence, there has been some concern about the amount of cadmium deposited in human tissue as a result of smoking. Lewis et al.,[59] seems to have done the most recent work in this area. Ignoring certain questions about their experimental methods, analysis of their results indicates that:

- In the absence of other factors, the total cadmium burden of moderate to heavy smokers is about two and a half times that of nonsmokers.
- In the absence of other factors, the total body burden of ex-smokers and of other kinds of smokers is about one and a half times that of nonsmokers.

These assumptions break the population down into three groups: (1) nonsmokers; (2) ex-smokers, light smokers, and others; (3) moderate to heavy smokers. Since we are primarily concerned with long-term exposures, we have defined the distribution of the three classes in terms of the age 50 population, making a midpoint interpolation between data on smoking habits for 1959 and 1965, and taking into account gender-related smoking habits.[60] The percentage of nonsmokers is taken to be 65 percent, the percentage of light smokers is taken to be 10 percent, and the percentage of moderate to heavy smokers is taken to be 25 percent.

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[59] G. P. Lewis, W. J. Jusko, and L. L. Coughlin, "Cadmium Accumulation in Man: Influence of Smoking, Occupation, Alcoholic Habit, and Diseases," J. of Chronic Diseases, Vol. 25, pp. 717-26 (1972).

Thus most Americans acquire cadmium mainly as a result of ingestion (and, for smokers, through smoking), rather than through breathing of cadmium in air. Average total rates are equivalent to 0.3 $\mu g/m^3$ air concentrations for smokers and upwards of 1 $\mu g/m^3$ for heavy smokers.

Figure 7-1 presents the basis for relating cadmium-produced mortalities to cadmium exposures. The figure reflects estimates for cadmium in food, water, tobacco, and air, which were converted to equivalent air exposure (expressed in equivalent $\mu g/m^3$) and multiplied by the years of exposure. Units in the abscissa are labeled "equivalent" μg-years/m^3 because of the various routes by which cadmium can enter the body, and because, even with actual cadmium dust in air, the exposure need not be full time (e.g., as in industrial exposures).

Dose-Damage Lower Limit

The lower dose-damage line was established from clinical studies of abnormal amounts of protein in the urine (proteinurea) of workers exposed to high cadmium air concentrations. Worker symptoms were then related to actuarial data on death rates from proteinurea. This clinical function seems reasonably well-based, but it presents only one of the many potential causes of cadmium mortality. To estimate dose, the mean time

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[60] E. Hammond and L. Garfinkel, "Changes in Cigarette Smoking 1959-1965," Am. J. Public Health, Vol. 58, No. 1, pp. 30-45 (January 1968).

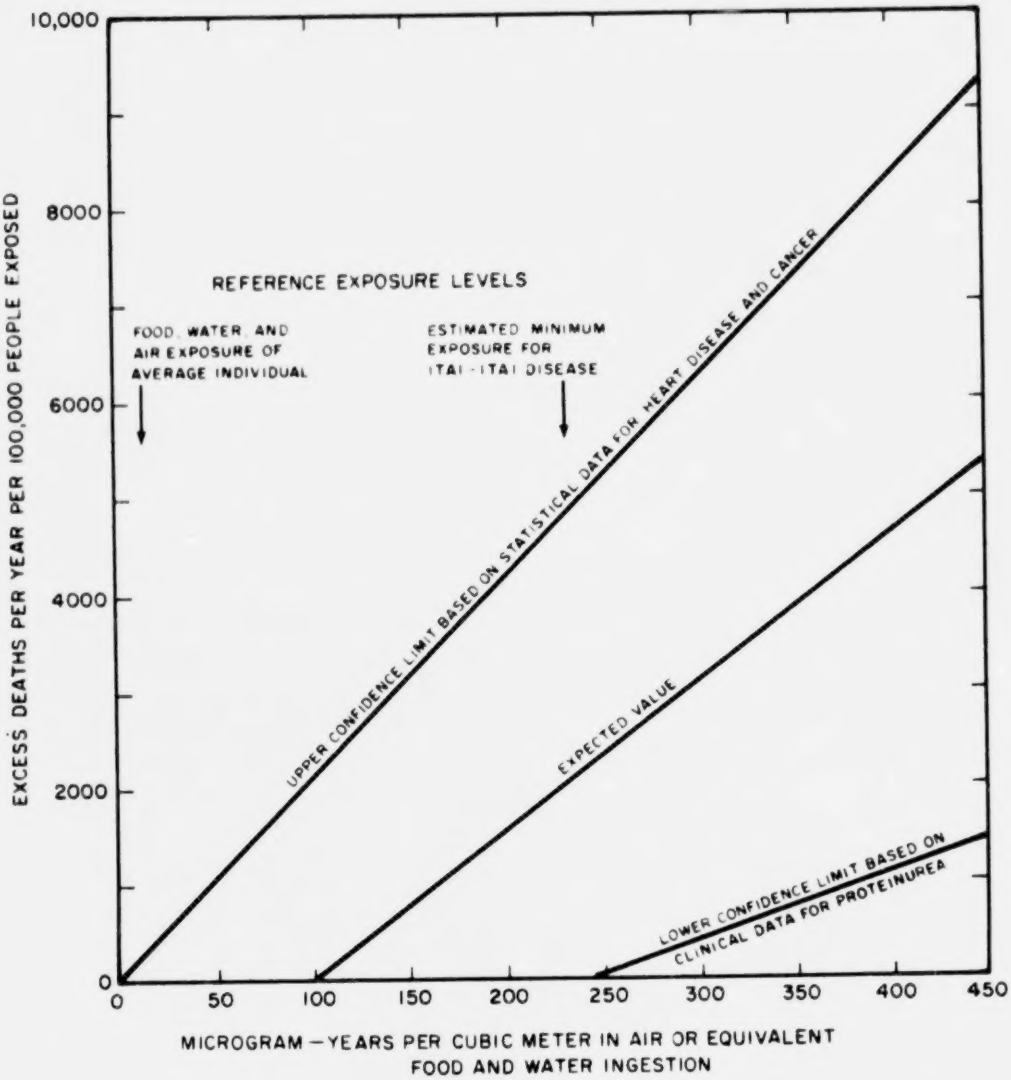

FIGURE 7-1 CADMIUM CUMULATIVE LIFETIME EXPOSURES VS. INCREASED MORTALITIES

of employment for the workers was determined by the research team led by Lauwerys[61] from company records, and multiplied by his estimate of average cadmium dust concentration in the air. The workers were exposed to cadmium in the factories roughly one-fourth of the time during their employment. To generalize on these results, we assume that the Lauwerys subjects were only exposed to normal amounts of cadmium in air, water, and food when away from the factory.

Mortalities associated with proteinurea are based on data appearing in a U.S. Public Health Service report.[62] That report estimated that if the entire population were given a scanning test for excess proteinurea there would be 600,000 positive results, and the expected annual excess deaths in the group with positive test results would be 14,500: a rate of 2,417 per 100,000. To obtain the rate for cadmium workers, we must multiply this excess death rate by the fraction of exposed workers who have proteinurea. Results of the calculation are shown by the lower line in Figure 7-1. Its straight line form was considered adequate for the purpose, considering the variability of exposure times and the unknown error in the cadmium concentration estimates.

Dose-Damage Upper Limit

The high-risk estimate of Figure 7-1 was obtained from studies by Hickey[63] and Carroll[64] of the relation of the cadmium content of urban air to disease of the cardiovascular system, and from Berg and Burbank's study[62] of the relation of cadmium in water to cancer. The data are combined into a single curve, and the uncertainties associated with this curve are discussed. As will be seen, both results may only be correlations rather than demonstration of cause and effect.

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[61] R. R. Lauwerys et al., "Epidemiological Survey of Workers Exposed to Cadmium," Arch. Environ. Health, Vol. 28, No. 3, pp. 145-8 (March 1974).

[62] "Kidney Disease Program Analysis," a report to the Surgeon General, Public Health Service Publication No. 1745 (1967).

[63] R. J. Hickey, E. P. Schoft, and R. C. Clelland, "Relationship Between Air Pollution and Certain Chronic Disease Rates," Arch. Environ. Health, Vol. 15, No. 6, pp. 728-38 (1967).

[64] R. E. Carroll, "The Relationship of Cadmium in the Air to Cardiovascular Disease Death Rates," J. Amer. Med. Assoc., Vol. 198, No. 3, pp. 267-70 (17 October 1966).

Using statistical data from the public Health Service, Hickey and Carrol derived a mathematical relationship that indicated that people living in urban environments with a high cadmium content suffer a higher death rate from heart disease than people living in a low cadmium environment.[63, 64, 65] Health effects considered included chronic and unspecified nephritis and other renal sclerosis (International Classification of Diseases 592-594), diseases of the heart (400-402, 410-443), diseases of the cardiovascular system (330-334, 400-468), arteriosclerotic heart disease (420), hypertensive heart disease (440-443), diabetes mellitus (260), general arteriosclerosis (450) and malignant neoplasms of the respiratory system (160-164). The more important regression equations indicated statistically significant correlations between the incidence of diseases of the heart and the concentrations of cadmium in the urban air of most major U.S. cities.

Other investigators have disputed these conclusions by claiming (1) faulty analytical techniques, or (2) stronger statistical correlations with population density. However, our intensive review indicates that the evidence based upon statistical inferences is reasonably well-founded and cannot be ignored. At the same time, the Hickey and Carroll data cannot be accepted literally. If their data were extrapolated to the maximum exposure found in the Lauwerys data, 463 μg yr/m^3 over a 28-year period, fewer than one percent of the subjects would have survived. (The principal assumptions used in this extrapolation are that any heart deaths in excess of 280 per 100,000 per year are due to cadmium in air, that the currently reported concentrations represent the endpoint of a linear buildup over 50 years, and that the excess death rates apply to people 50 years or older.) The observation leads us to believe that in the urban environment, the observed air concentration correlation with heart mortalities is a surrogate for some more basic effect such as that of arsenic, rather than a direct cause.

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[62] J. W. Berg and F. Burbank, "Correlations Between Carcinogenic Trace Metals in Water Supplies and Cancer Mortality," pp. 249-64 in "Geo-Chemical Environment in Relationship to Health and Disease," H. C. Hopps and H. L. Cannon, editors, Ann. N.Y. Acad. Sci., Vol 199 (28 June 1972).

[63] "Vital Statistics of the United States 1969, Vol. II-Mortality, Part B," Public Health Service, National Health Center for Health Statistics (1973).

Under the current view, cadmium normally enters the human system primarily via food, and secondly through water. Since the food consumed in most urban environments normally comes from a much wider and primarily nonurban region, we have assumed that urban air readings are partially correlated with water concentrations, but not with food concentrations. To treat the water relationship quantitatively, we have assumed that for every additional nanogram per m^3 in air above the "uncontaminated" level of 1 ng/m^3, the local water concentration will increase 0.5 μg/liter above its "uncontaminated" level of 1 μg/liter.

Table 7-2 shows our derivations from the Hickey-Carroll estimates of excess heart death rates for people over 50. It incorporates our assumptions concerning cadmium intakes from all three sources--air, water, and food--for urban areas, when the air readings are 0.001 and 0.04 μg/m^3, respectively.

Another statistical correlation, by Berg and Burbank[illegible] has implicated cadmium in water as a factor in all cancer (International Classification of Diseases, pp. 140-205). Since neither regression equations nor original data were given, the dose-damage correlation was derived by

Table 7-2

CADMIUM INTAKE AND HEART DEATH RATE CALCULATIONS

	Reference Level	Elevated Level
Recent environmental air concentrations ($\mu g/m^3$)	0.001	0.04
Average in air ($\mu g/m^3$) over 50 years	0.001	0.02
Average ingested in water (μg/day)	0	20
Average ingested in food (μg/day)	50	50
Total ingested (μg/day)	50	70
Ingested equivalent air concentration ($\mu g/m^3$)*	0.301	0.422
Total equivalent air concentration ($\mu g/m^3$)	0.302	0.442
50-year equivalent air exposure (μg-yr/m^3)	15.1	22.1
Corresponding annual heart death rate (per 100,000)	280	406

*Using mean estimate of 1/166 for conversion factor.

Source: Derived by SRI from Hickey data on heart mortalities regression from Berg's graph showing the colon and rectum mortalities (153-154) as a function of cadmium in water. The total cancer mortality rate was derived by multiplying Berg's dose-damage points by the ratio of total cancer deaths to the colon and rectum cancer deaths, as reported in the U.S. Vital Statistics[68] for 1969.

As was the case for the heart data, there are good reasons why the Berg data cannot be interpreted literally. In the first place, our reference level for the normal cadmium content in water, 1 µg/liter is significantly higher than the values used by Berg and Burbank, which averaged only 0.11 µg/liter of cadmium. Secondly, if the reported water values are converted to equivalent $\mu g\text{-}yr/m^3$, a dose-damage slope steeper even than that from the heart data is obtained. The Lauwerys subjects would have been less likely to survive cancer than they would have heart disease. Thus, the best hypothesis for the demonstrated correlation between basin-wide cadmium concentration in water and excess cancer mortalities is that the concentration values must be a surrogate for some more basic effect, rather than a direct cause.

The most important analytical condition for cancer mortalities has to do with how the basin-wide observations are related to the amounts of cadmium ingested via air and food. The basic assumptions used here are that the effect of air is negligible and that there is a linear relation between water and food. This set of assumptions is based on (1) the known quantities of cadmium people inhale or ingest, via air, water, and food, and (2) the hypothesis that water concentrations affect food concentrations for local residents.

The dose-damage results for cancer mortalities were combined with the result for heart mortalities to produce the upper line in Figure 7-1. Confidence limits were calculated for each source curve, but since the range of the confidence limits was small relative to the spread between source curves, these limits are not considered further. The large spread between the source lines is, unfortunately, representative of the current state of the art in estimating the potential health effects of cadmium pollution. In view of this last observation, we have used these curves as bracketing, rather than as additive, measures of cadmium-related mortalities. An expected value curve was constructed by bisecting the vertical distance between the source curves.

Effects of Population Mobility on Cadmium Mortalities

The cadmium distribution processes modeled in Chapter 6 indicate that the hazard is localized. Thus, only the community in which the emission takes place is likely to show significant increases over background. As a consequence, both the number of people who have lived in the community and the length of time they have lived there are important considerations in determining the health risks associated with the cadmium emission source.

In the United States, roughly 20 percent of the population moves every year, but only 6.7 percent of U.S. population makes an out-of-county move. We will assume that only an out-of-county move places a person beyond the effective range of the emitter. Figure 7-2 shows the cumulative distribution of exposure times for the population currently living in a community with a significant cadmium emitter. The figure shows that after 10 years less than 50 percent of the original population remain, after 30 years less than one-tenth remain, and after 50 years less than two percent remain. These numbers illustrate the fact that although body burden can increase until age 50, very few people will spend all of those years in a cadmium-polluted environment.

To account for most people's limited time exposure, we make the simplifying but conservative assumption that the emitter has been in the community long enough to reach a steady-state environmental contamination level, and that the community's population also is in equilibrium. Thus

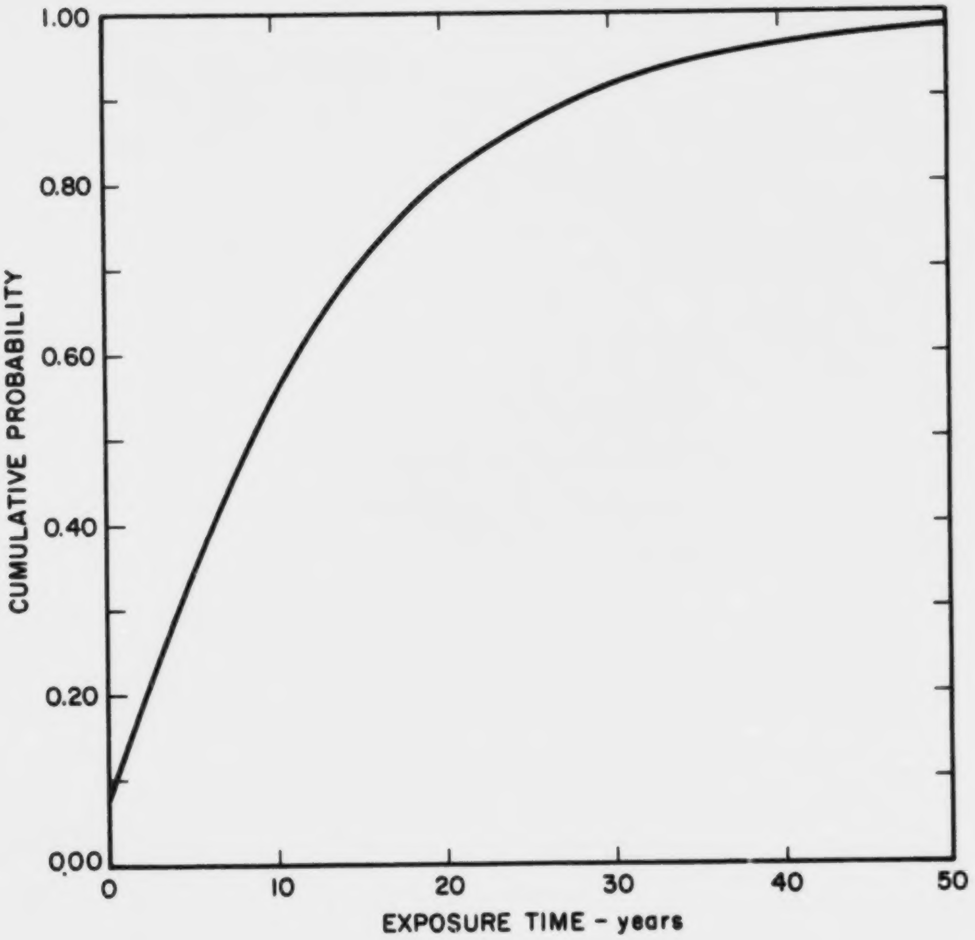

FIGURE 7-2 CUMULATIVE PROBABILITY OF A RESIDENT LEAVING COUNTY OVER TIME

each year a group of people who lived in the community no longer acquire an excess body burden because they move, or because they reach age 50. Of the community's population 6.7 percent move away and 1.1 percent reach age 50 each year, so that 7.8 percent cease collecting meaningful exposures. Under the steady-state assumption, they are replaced by a new 7.8 percent of whom 6.7 percent move into the community and 1.1 percent are born there.

It will also be conceptually useful to assume that (1) all people leave or enter the community at the same time, say the beginning of each year and (2) that, at most, people will only have one significant exposure to cadmium; i.e., if they leave they do not return. In the present context, both of these assumptions have a negligible effect on the outcome.

Let $n_t(J)$ be the number of people who have been exposed for t years at time J, and let P be the probability of terminating exposure after any given year. Since the exposure process has reached equilibrium.

$$n_t(J+1) = n_t(J) \tag{7-1}$$

for any t and J. Therefore we can drop the J notation and note that at the end of each period, n_tP will terminate their exposure. The number of people who will be exposed for t+1 years is given by

$$n_{t+1} = n_t - n_tP = n_t(1-P) \tag{7-2}$$

and by iteration from time 0

$$n_t = n_0(1-P)^t \tag{7-3}$$

Now at any given time the number of people in the various year groups must sum to the total size of the population being exposed, S, i.e.,

$$\sum_{t=0}^{49} n_t = S \quad . \tag{7-4}$$

Combining Equations (7-3) and (7-4) and converting the series, we obtain

$$S = \frac{n_o\left[1-(1-P)^{50}\right]}{P} \approx \frac{n_o}{P} \quad . \tag{7-5}$$

Thus we can define n_o by

$$n_o = PS \quad . \tag{7-6}$$

Let f_t be the fraction of the population with an exposure of t years

$$f_t = n_t/S \quad . \tag{7-7}$$

Combining Equations (7-3), (7-6), and (7-7) we obtain

$$f_t = P(1-P)^t \quad . \tag{7-8}$$

Finally, if we symbolize the fraction of total population with an exposure of t or less years by F_t, we can write

$$F_t = \sum_{t=0}^{t} f_t = 1 - (1-P)^{t+1} \quad . \tag{7-9}$$

This last result is the equation used to compute the cumulative probability result shown in Figure 7-2.

The implication of interest is the effect of operating a cadmium plant without improved controls for another year. Continuing operations will of course expose each individual in the local group to one more year of dosage, but the individual effects are difficult to summarize because prior exposures vary. An easier way of measuring the overall effect is to compare the dose distributions of the local population at the end of the extra year for the alternatives of continued operation versus shutdown of the plant.

If the plant shuts down at the beginning of the year, then all dosages remain the same as at time t_o. If it continues to operate, all residents except those who move away or reach age 50 advance one year in exposure and a new group of n_o people receive their first year of exposure. Since the system will continue to operate in environmental equilibrium, the number of people being exposed will remain the same as before time t_o, but the "graduates," (those leaving and reaching age 50) will account for the incremental dose burden caused by the year of continued operation. Let n'_t, the difference between the number of local residents with t years dose at the beginning and those with t+1 years dose at the end of the continued year of operation, represent these incremental graduates. Thus,

$$n'_t = n_t - n_{t+1} = n_o\,(1-P)^t - n_o\,(1-P)^{t+1} \quad . \tag{7-10}$$

Summing over all year groups gives us the sum of the incremental graduates, S'

$$S' = \sum_{t=0}^{49} n'_t = n_o[1 - (1-P)^{50}] \approx n_o \quad . \tag{7-11}$$

The distribution of exposure times among the graduates can be represented by the cumulative fraction F_t.

$$F_t' = \sum_{t=0}^{t} \frac{n^t}{S'} = \frac{n_o - n_o(1-P)^{t+1}}{n_o\left[1-(1-P)^{50}\right]} \approx 1 - (1-P)^{t+1} \quad . \qquad (7\text{-}12)$$

Note that this result has the same form as Equation (7-9). Equations (7-11) and (7-12) together completely describe the effect of operating the plant for one additional year. Equation (7-11) tells us the net number of people with increased exposure times is equal to n_0, which Equation (7-6) equates to the mobility percentage P (7.8 percent in our case). Equation (7-12) gives the distribution of exposure times for these people, which turns out to be the distribution of Figure 7-2.

Overall Cadmium Mortalities

The normal contribution from the environment must be added to the local air effects. As noted, this contribution is dominated by the food component which is assumed to contribute 50 μg per day--equivalent to raising the environmental air level by 0.3 $\mu g/m^3$. We should add that this portion of the body burden is acquired from birth until age 50, rather than just during the time spent in the locale containing a cadmium emitter.

Given the above information, and some exposure level in the polluted local area, we can compute the body burden in equivalent $\mu g\text{-}yr/m^3$. To relate this value to a decrease in life expectancy, we proceed as follows. Body burden is converted to number of excess deaths per 100,000 from Figure 7-1. Most of these deaths are in the over-50 age group; excess deaths from cadmium prior to age 50 are trivial. Since the over-50 population comprises about 25 percent of the population, we must multiply the excess death rate for the general population by a factor of 4 to determine the excess rate in the over-50 group. The reciprocal of the normal plus excess death rate equals their average life expectancy. Subtraction of this life expectancy from 20 years (the average age of dying for people at 50 was conservatively taken to be 70) then gives the life shortening due to the extra cadmium exposure.

Risks of Cadmium to the General Population

We have chosen to state the health risks of cadmium in terms of life loss. The direct and indirect risks of illness might also be considered, but these other economic effects are generally smaller, particularly for such risks as cancer and circulatory diseases.[67] Furthermore, the "willingness to pay" concept of risk evaluates all subjective safety risks in terms of mortality cost, so the other risks can be neglected.[68,69]

To determine the number of people exposed to cadmium around zinc smelters we have assumed a constant population density of 100/km^2 and integrated their exposures over (1) distance and (2) time spent in the area. The mobility model implies that each year 7.8 percent of the population of a risk area cease to acquire additional body burden. The total annual life shortening suffered by the departing 7.8 percent serves as the measure of annual life shortening effects among all the people exposed.

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[67] D. P. Rice, "Evaluating the Cost of Illness," HEW, Public Health Service, Table 3.1 (May 1966).

[68] E. J. Mishan, "Evaluation of Life and Limb: A Theoretical Approach," J. Political Economy, Vol. 79, No. 4, pp. 687-706 (July-August 1971).

[69] J. Hirshleifer, et al., Applying Cost-Benefit Concepts to Projects Which Alter Human Mortality, Univ. of Calif., Los Angeles (November 1974).

To carry out the integration process we proceed as follows. The people at risk are partitioned into groups with similar distance and duration of exposure, using Figures 6-2 and 7-2. We calculate the number in each group and their average dose. With the aid of Figure 7-1, the excess death rate is obtained and added to the normal death rate, 0.05. The reciprocal of this sum is the average life expectancy (for 50-year-old people). Subtracting life expectancy from 20 years, the normal life expectancy, gives us the average life shortening for the group. Summing the product of number of people times years lost over all groups at risk produces the total number of person-years of life shortening. To obtain the average number of years of life shortening per person, we divide by the total number of people at risk.

Results of integrating by this method for U.S. smelters indicates that for each year we continue to operate the smelters, 33 people among the U.S. population lose 166 person-years from life shortening. The average years lost per fatality is 5 years.

By using the same methods, we conclude that municipal incinerators constitute a much less serious cadmium problem. The area of significant smelter effects was found to be less than 100 km^2. In this range the incinerator generated pollutant levels are less than 1/1000 of the smelter-generated incinerator levels, so instead of the 166 person-years quoted above the life shortening is less than one (and probably less than one-tenth) person-year.

Asbestos Example

In this subsection, the data on asbestos air concentrations are combined with dose-damage relations to arrive at the risks to health from asbestos.

Significant data exist on several asbestos-related health effects. These data have been obtained from studies of various types of asbestos workers, and have been used to relate estimates of exposure to the various health effects. Furthermore, the principal mode of entry into the human body for asbestos appears to be via the lungs (EPA is currently supporting work to better define the hazards of other ingestion modes). Consequently neither a basic body burden model, nor a system for converting ingested or tobacco-related asbestos to equivalent amounts in the air is required.

The principal known health effects produced by asbestos are:

- Respiratory system diseases, such as pneumocosis, pulmonary fibrosis, and asbestosis.
- Respiratory system cancers, such as those of the lung, bronchus, trachea, and pleura.
- Mesothelioma: a rare cancer of the chest cavity associated primarily with asbestos exposure.

For asbestos workers, mesothelioma appears to be the most significant asbestos-related cause of death. Other cancers, taken as a group, appear to be roughly comparable, while asbestosis produces about one-third as many deaths. Asbestosis also produces a significant number of workers requiring treatment or compensation, but these effects are not included in the present analysis. Various studies of the ingestion of asbestos, primarily via water have concluded that in normal circumstances, the amounts involved are too small to produce cancer.

Prior to the discovery of high concentrations of asbestos in the drinking water of communities near Duluth on Lake Superior, an asbestos study was undertaken by the American Water Works Association Research Foundation to evaluate whether the use of asbestos-cement pipe was a health hazard.[70] It concluded that although such pipe was a potential source, the highest concentration of water-borne asbestos would result in 0.07 gram ingested in 60 years. (Amounts inhaled from industrial exposures over a similar period, according to the Enterline group, could amount to 336 grams.) The Water Works study concluded that there was no convincing medical evidence that these small concentrations in water would produce a risk of cancer. Another group studying the Duluth situation arrived at a similar conclusion.

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[70] "A Study of the Problem of Asbestos in Water," by the American Water Works Association Research Foundation, Am. Water Works Assn., Vol. 66, No. 9, Part 2, pp. 1-22 (September 1974).

The only study implying that ingested asbestos could cause cancer suggested that the excessive stomach cancers exhibited by a selected Japanese population was caused by the use of talc containing asbestos as a polishing compound for rice.[71] As a result of the negative findings of animal feeding[70] and the lack of corroborative data from other statistical studies such as that of Masson,[72] it was decided to exclude asbestos ingestion as a variable in this study.

Dose-Damage Relationship

Figure 7-3 is the basis for relating asbestos mortalities to the pollution conditions estimated by the methods of Chapter 6. The lines shown represent excess death rates caused by the indicated asbestos doses, measured in nanogram-years per cubic meter. Death rates are obtained by summing over the individual causes mentioned above. Since most measurements are related to asbestos fibers with a length greater than 5 microns, the current industrial standard of five fibers per cubic centimeter has been converted to the grams per cubic meter dosage measure. The confidence limits indicate the uncertainty in death rate associated with a

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[71] R. R. Merliss, "Talc-Treated Rice and Japanese Stomach Cancer," Science, Vol. 173, pp. 1141-2 (17 September 1971).

[72] T. J. Masson, F. W. McKay, and R. W. Miller, "Asbestos-Like Fibers in Duluth Water Supply--Relation to Cancer Mortality," J. Amer. Med. Assn., Vol. 228, No. 8, pp. 1019-20 (20 May 1974).

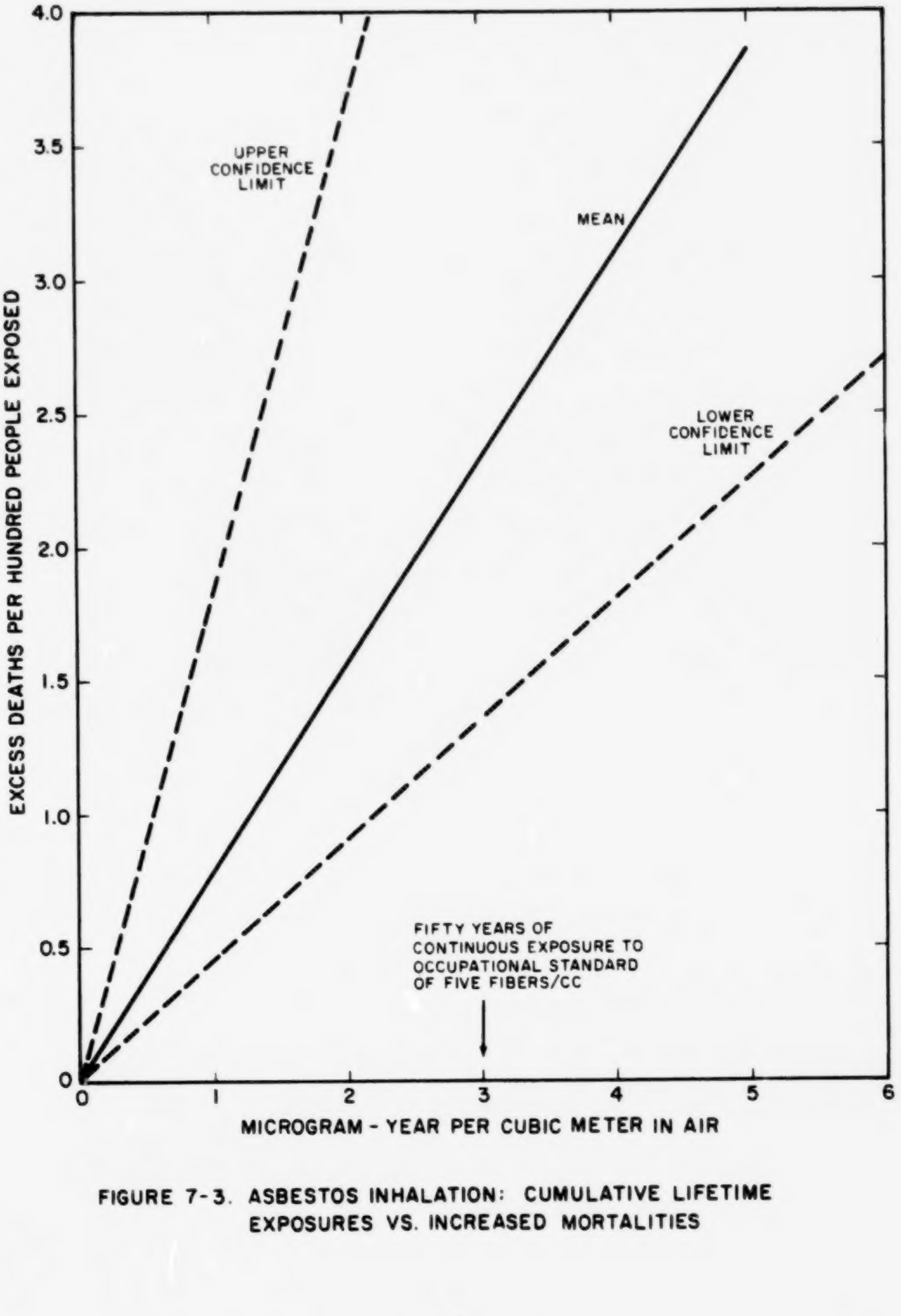

FIGURE 7-3. ASBESTOS INHALATION: CUMULATIVE LIFETIME EXPOSURES VS. INCREASED MORTALITIES

given dose estimate. Since the death rate is an excess rate, associated with some level of asbestos dose, an excess rate of zero must be associated with a zero dose level. However, we have no idea of what the confidence limits look like in the low dose region.

Four dose/damage diagrams for respiratory diseases, mesothelioma, other respiratory cancers, and asbestosis were derived from industrial data of Enterline,[73] Roach,[74] Bruckman,[33] and Selikoff.[75] The diagrams are shown in Figures 7-4, 7-5, 7-6, and 7-7. Three of them are curvilinear rather than straight line approximations to the original data, but linear estimates have been used to synthesize overall asbestos mortalities in Figure 7-3. All show asbestos exposures in fiber-years per cc (for fibers sizes greater than 5 microns) versus death rates, except the last which gives rates of asbestos illness.

We encountered several uncertainties in the original data. The Enterline doses for cancer and respiratory diseases were measured in millions of particles per cubic foot (MPPCF) by the "impinger" method. In contrast, the asbestosis dose/damage curve was developed using a membrane filter and counting asbestos fibers greater than 5 microns in length. NIOSH has recently accepted the latter data as the best available and has established U.S. working place standards in terms of fibers per cc (longer than 5 microns).

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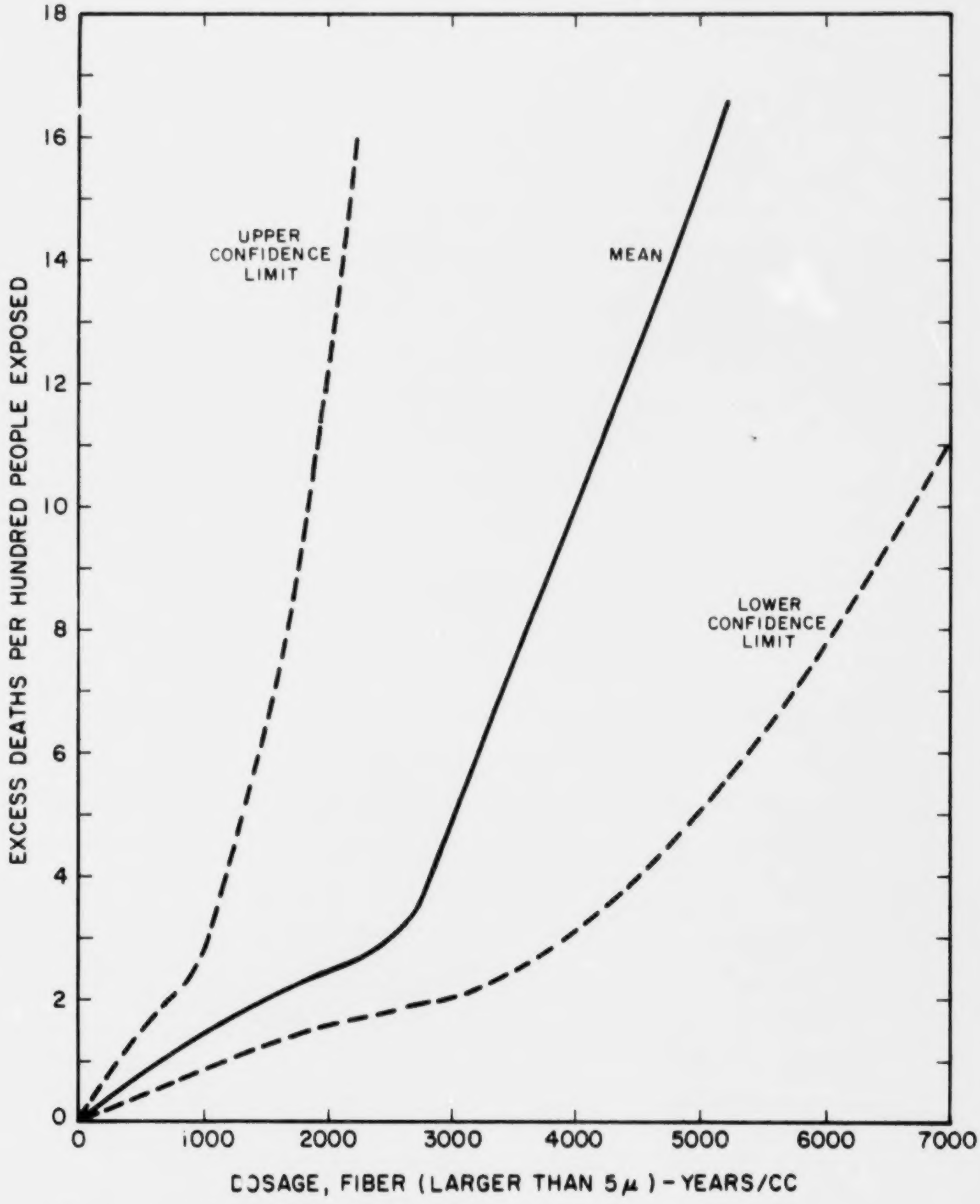
[73] P. Enterline, P. DeCoufle, and V. Henderson, "Mortality in Relation to Occupational Exposure in the Asbestos Industry," J. Occup. Med., Vol. 14, No. 12, pp. 897-903 (December 1972).

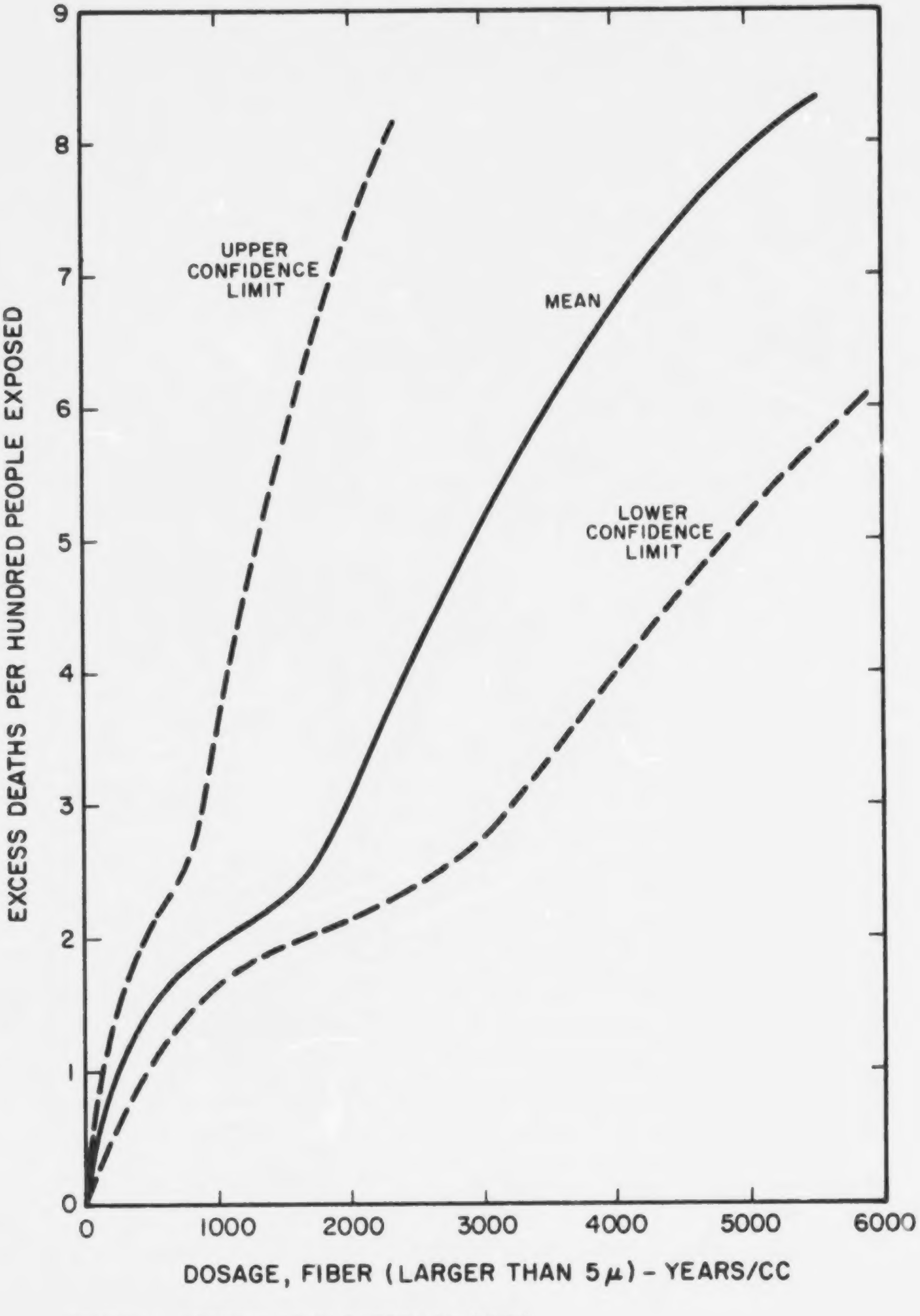
[74] S. A. Roach, "Hygiene Standards for Asbestos," Ann. Occup. Hyg., Vol. 13, pp. 7-15 (1970).

[75] I. J. Selikoff, "Asbestos Criteria Document Highlights," ASSE Journal, pp. 26-33 (March 1975).



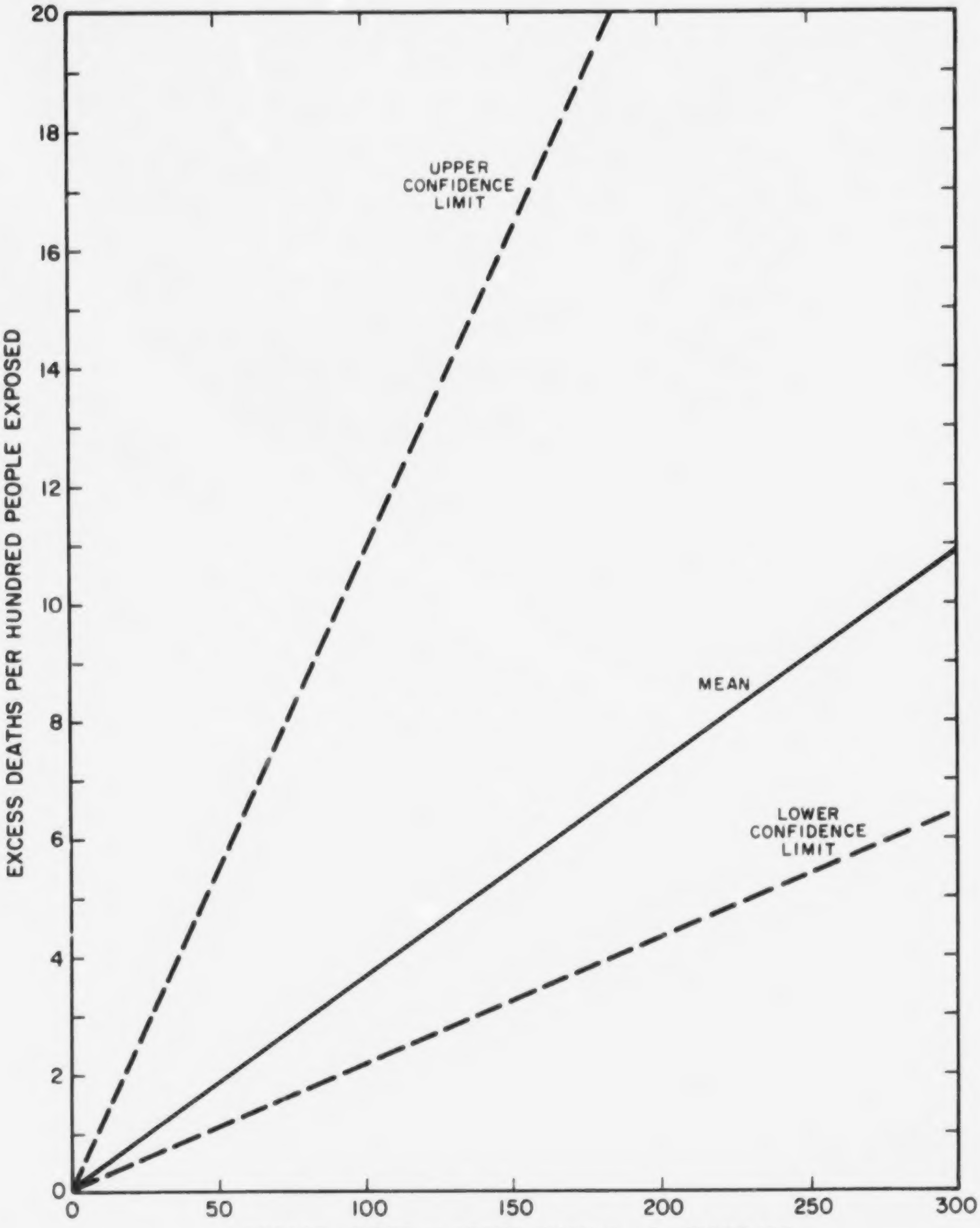
SOURCE: DERIVED FROM ENTERLINE (1972)

FIGURE 7-4. RESPIRATORY SYSTEM DISEASE MORTALITIES CAUSED BY ASBESTOS DOSAGES



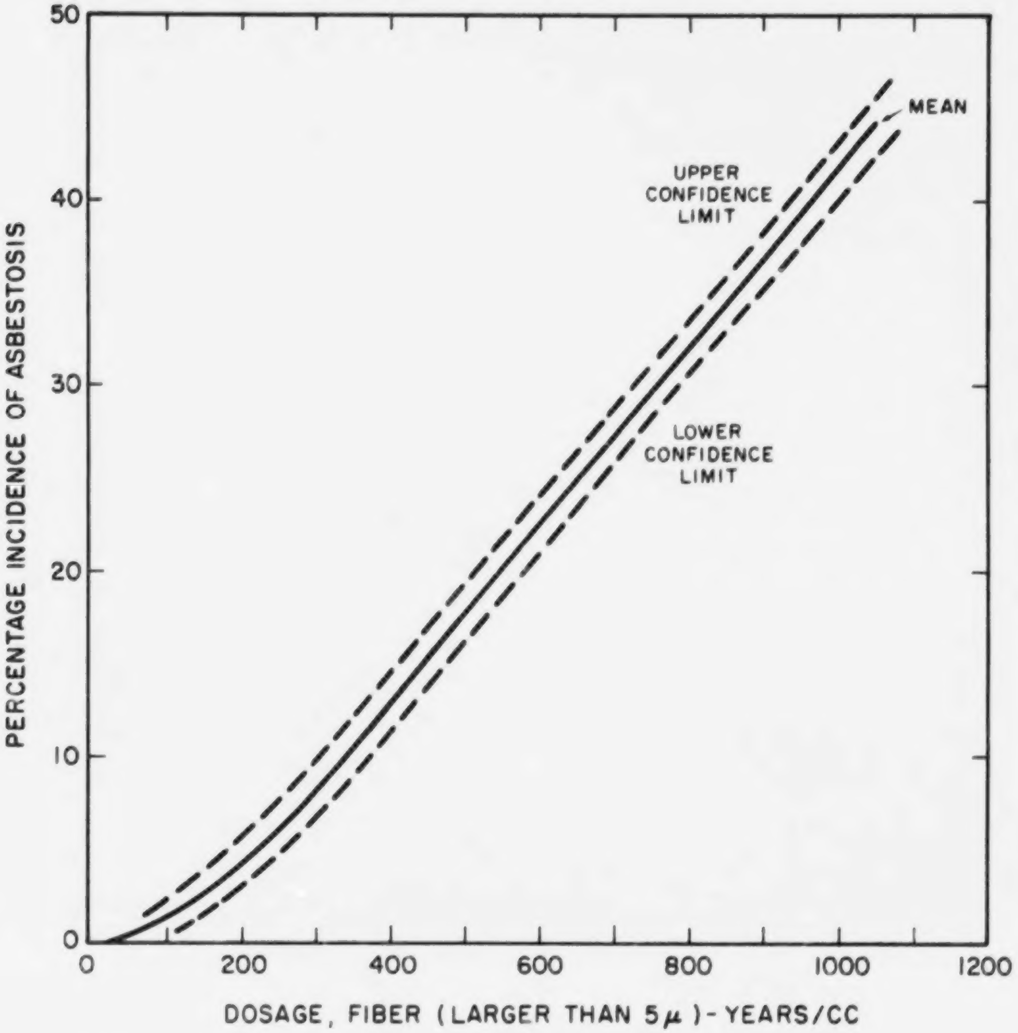
SOURCE: DERIVED FROM ENTERLINE (1972)

FIGURE 7-5. CANCER (EXCEPT MESOTHELIOMA) MORTALITIES CAUSED BY ASBESTOS DOSAGES



SOURCE DERIVED FROM SELIKOFF (1974), BRUCKMAN (1974)

FIGURE 7-6 MESOTHELIOMA MORTALITIES CAUSED BY ASBESTOS DOSAGES



SOURCE: DERIVED FROM ROACH (1970)

FIGURE 7-7. ASBESTOSIS SYMPTOMS CAUSED BY CHRYSOTILE ASBESTOS DOSAGES

To reduce the Enterline dosage data from MPPCF-years to fiber-years/cc the conversion factors suggested by Ayer[76, 77] were used. Unfortunately, Ayer presents a grand mean conversion ratio (fibers/MPPCF = 5.4) from measurements covering a range of almost four to one. They were made at four different plants that employed five different operations to process asbestos fibers. The range in conversion factors placed wider limits on the data than the uncertainty in dosages, so the conversion ratios may be assumed to be measures of reliability of the data. In Figures 7-4 and 7-5, the grand mean conversion factor fibers/MPPCF = 5.4 was used as the best estimator of the mean, and the extreme conversion factors were used as confidence limits.

There were other data reduction problems. For asbestosis, the British (Roach,[79] Lane[78]) include a confidence level of one percent risk of asbestosis in their estimate of the exposure. The values estimated are a mean = 112 fiber-years/cm^3 and lower confidence (two-sigma) limit of 51 fiber years/cm^3 at the 90-percent level, or a confidence multiplier of about 2. The Enterline data on cancer and respiratory diseases implied a two-sigma confidence limit multiplier of about 1.3.

The mesothelioma diagram presents the largest uncertainty of all because of conflicting statistics in two references, both attributing their original data to the same source. Our derivation from data reported

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[76] H. D. Ayer and J. R. Lynch, "Motes and Fibers in the Air of Asbestos Processing Plants and Hygienic Criteria for Airborne Asbestos," pp. 511-22 in Inhaled Particles and Vapours II (Pergamom Press, 1965).

[77] H. E. Ayer et al., "A Comparison of Impinger and Membrane Filter Techniques for Evaluating Air Samples in Asbestos Plants," pp. 274-87 in Biological Effects of Asbestos, Ann. N.Y. Acad. Sci., Vol. 132 (December 1965).

[78] R. E. Lane et al., "Hygiene Standards for Chrysotile Asbestos Dust," from the Committee on Hygiene Standards of the British Occupational Hygiene Society, Ann. Occup. Hyg., Vol. 11, pp. 47-69 (1968).

by Bruckman[35] yielded a dose-damage curve five times as steep as the curve from data reported by Selikoff.[79] If these are considered as a sample of two in a log normal distribution, the two-sigma confidence limits will be multiplying and dividing factors of 10 about the geometric mean.

Conversion of industrial exposures into units that are consistent with continuous exposure to ambient air concentrations of asbestos requires a conversion from fibers/cm^3 (greater than 5 μ) into absolute weight concentrations. The convention of Bruckman was used. Dose-damage diagrams constructed by this method provide the basis for the total fatalities predicted in Figure 7-7.

Another major uncertainty in the above data is the determination of the dosage, since from 20 to 40 years elapse before detrimental health effects become apparent. Throughout the development of the dose/damage diagrams in this report, one of the basic assumptions was that the dosage occurred year after year, throughout the workers lifetime. However, Selikoff points out that "years of exposure" are not necessarily synonymous with "years from onset of exposure." An important variable is lacking from our predictive dose-disease response diagram--the residence time of the asbestos in the lungs. Therefore, such cancers as mesothelioma may be caused by extremely short exposures that trigger the onset of the disease some 20 to 30 years later.

Another explicit assumption involved in the development of our dose/response curves is that there is no safe level of exposure (i.e., no threshold limit) to asbestos dust. We extrapolated the industrial data linearly to zero dosage at zero damage. Also this extrapolation is made below the lowest industrial exposure data. It is assumed that this treatment of the data must have some degree of validity as a predictive model since a survey of 17,800 asbestos insulation workers gave total fatalities that are in plausible agreement with the curve used here.[79]

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[79] I. J. Selikoff, "Asbestos Criteria Document Highlights," ASSE Journal, pp. 26-33 (March 1974).

Risks of Asbestos

As a first approximation we have assumed that population movement will not affect asbestos dose estimates--since the industrial and other sources of asbestos pollution are rather widely spread. Also as a first approximation, the treatment of life shortening should be the same as that used in the case of cadmium.

Inspection of Figure 6-3 will show that the maximum asbestos exposure level is about 20 ng/m^3. Thus a worst case for a 50-year exposure by the general public is 1,000 $ng/yr/m^3$. But the dose in Figure 7-3 is expressed in millions of nanogram years per cubic meter--a thousand times as severe. Extrapolating the best estimate line into the low dose region we find that the excess death rate per 100,000 exposures is less than one. Note this is a result to which we can attach, at best, order of magnitude confidence. However, if the mean curve is at all representative, then our result indicates essentially zero health effects for the asbestos air exposures to the general population specified in Figure 6-3.

The result shows negligible hazards whether the exposed population densities are 2,374/km^2 as estimated in Chapter 4 or 200/km^2 as estimated in Chapter 6. But it does not, of course, indicate that hazardous doses could not be obtained by a relatively few mine, factory, construction workers, and others who are in close personal contact with asbestos.

Chapter 8

COMBINING RISK, BENEFIT, AND OTHER CONSIDERATIONS

Introduction

All of the data collected in the foregoing chapters are of little use for decision purposes until they can be formulated in some fashion that will permit comparison of the various considerations involved. The optimum manner of formulating the problem depends on how and by whom the choice is to be made, which in turn depends on the environment of the decision situation.

Because these are largely questions of human beliefs and values, it should be axiomatic that the choice of alternatives rest with a human decisionmaker, rather than with a fully programmed machine or procedure. However, attempts to fully automate social choices have been suggested in so many decision methodologies that some caution is in order. The methodology illustrated here is not one that pretends independence of the human decisionmaker. Too many nonquantifiable, incommensurable, and incompatible factors are involved to expect that any standard procedure could be relied on to substitute for human judgment.

Alternative Criteria Formulation Methods

Some efficient protocol for arranging and comparing the data is obviously needed to help the decisionmaker deal with the complexities of the problem. Essentially, there are three methods of choosing from among alternatives. Simplest is the method of choosing on the basis of one parameter and ignoring all other considerations. As Chapter 2 illustrates, this is the method of "zero tolerance" and "permissible limit" types of standards that rely only on risk considerations. It is also the method of "best technology," which relies exclusively on economic or operational feasibility.

The second method is to attempt to combine all the important decision factors into one overall measure of value, such as money, lives, or "utility" and then to choose as above on the basis of which alternative has the most of this measure. An example is the method of conventional cost/benefit procedures, which assumes that all important factors can be expressed and then compared in dollar terms. As was explained in Chapter 2, the world is nearly always too complex for such a model. Even when two incommensurable parameters such as risk and benefit are combined as the two dimensions of a single diagram, they have only reduced the number of unknown parameters from n to n-1.

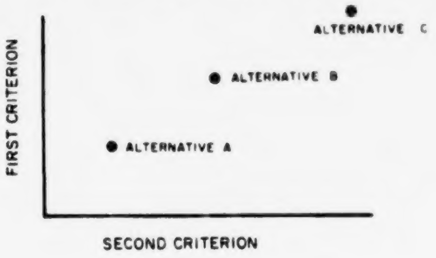
The third method, multiple criteria decisionmaking, incorporates the comparison procedures of the cost/benefit method and in addition uses these criteria as variables and constraints in special ways. Even this method is not generally able to array decision variables that are nonquantifiable or incommensurable with each other, but it does incorporate a wider and more realistic picture of most decision situations than the other two methods.

The Recommended Method

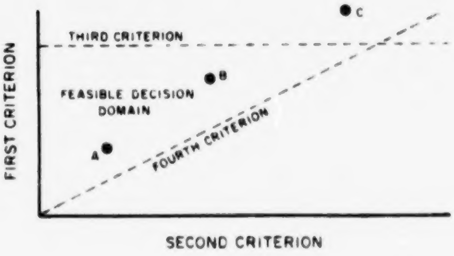
This third method is the one advocated in the present study. Expressed in its simplest logic, the multiple criteria method of formulating data for decisionmakers involves the following four types of considerations:

(1) The two dominant criteria to be compared and "traded-off" against one another--in this case, risk measured in lives lost and benefits measured in dollars--are quantified as in Chapters 5 and 7. Then their values for alternative actions of interest are compared as independent dimensions in a two-dimensional graph (see Figure 8-1A).

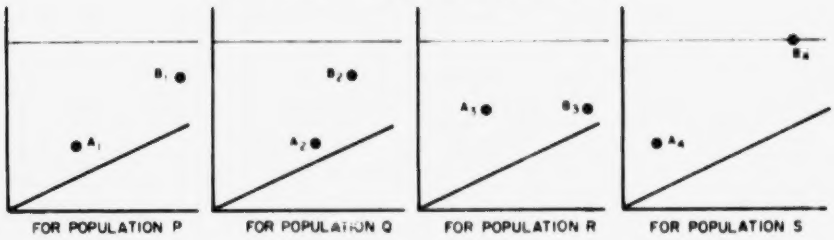
(A) COMPARISON OF TWO CRITERIA



(B) MULTIPLE CRITERIA COMPARISON



(C) DISTRIBUTIONAL CRITERIA COMPARISONS



(D) MATRIX DISPLAY OF SUPPLEMENTARY CRITERIA

CRITERION	QUANTITATIVE OR QUALITATIVE VALUE FOR			CONDITIONS AND QUALIFICATIONS
	ALTERNATIVE A	ALTERNATIVE B	....	
x				
y				
z				
....				

FIGURE 8-1. METHODS OF DISPLAYING DECISION CRITERIA

(2) Next, other incommensurable criteria, such as maximum limits in the risk, benefit or combined dimensions, can be added to enclose the possible decision domain. All values outside of this domain are infeasible (see Figure 8-1B).

(3) Several iterations of steps (1) and (2) can be made for different populations or for subgroups of the same population, to ensure that all population groups fall within the decision domain or meet other common criteria. Distributional aspects of multiple criteria problems, such as comparisons of trade-offs among different geographic areas, can be examined by this means (see Figure 8-1C).

(4) Finally, a catch-all array of criteria that relate to the decision problem but are not comparable to the multiple quantitative criteria can be constructed so that the decisionmaker will have recall access to all of the significant considerations that might be expected to influence his choice (see Figure 8-1D).

Handling Uncertainties

Treatment of uncertainties is of major importance for any of the criteria because the uncertainties are nearly always significant and are sometimes dominant. Furthermore, many of the analytical methods advocated here accentuate the influence of uncertainties, for example: (1) establishing criteria on the basis of cumulative factors each of which incorporates some uncertainty; (2) calculating the ratios of two different uncertain criteria; and (3) comparing the difference between uncertain criteria. As will be seen in the next chapter, many decision problems are more dependent on the resolution of uncertainties than they are on the comparison of expected values.

For these reasons, uncertainties have been estimated and cumulated in the preceding chapters according to estimates of confidence limits that are based (unless otherwise indicated) on assumed two-sigma deviations from the mean of a log normal distribution. These limits incorporate about 95 percent of the expected observations of the assumed distributions. Log normal distributions are assumed because they reflect proportional (rather than absolute value) uncertainties that are most characteristic of experimental and observational evidence. Also, log normal distributions best represent the extremely wide uncertainties (measured in orders of magnitude) that are sometimes found in the data, and they are convenient for combining the uncertainties of variables (such as dose and damage or benefit and risk) that must be multiplied or divided by each other.

To simplify the presentation of uncertainties for consideration by the decisionmaker, the two-sigma confidence limits are graphically illustrated as the upper and lower bounds of a band of confidence around the expected value.[80] If the criteria are shown in two dimensions, then the confidence limits in both dimensions can be combined to form an oval around the point that represents the expected value. Such limits are shown in Figure 8-2. (Other characteristics of the criteria shown in Figure 8-2 are discussed in the following sections.)

At the same time, one should not overemphasize the statistical accuracy of these methods of estimating and combining uncertainties. Many types of distributions cannot be well represented by the log normal function; also additive and other types of combinational operations cannot be easily performed. However, the current state of the art of uncertainty estimation for environmental policy-making is so primitive that these limitations seem minor compared to the extent of other unknowns. Such major unknowns as those buried in the imprecision of existing methods, the synergistic or inhibitory effects of combining uncertainties,

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[80] D. P. Tihansky, "A Cost-Risk-Benefit Analysis of Toxic Substances," presented at Early Warning Systems for Toxic Substances, Seattle, Washington, 31 January 1974; published in J. Environ. Sys., Vol. 4, No. 2, pp. 117-34 (Summer 1974).

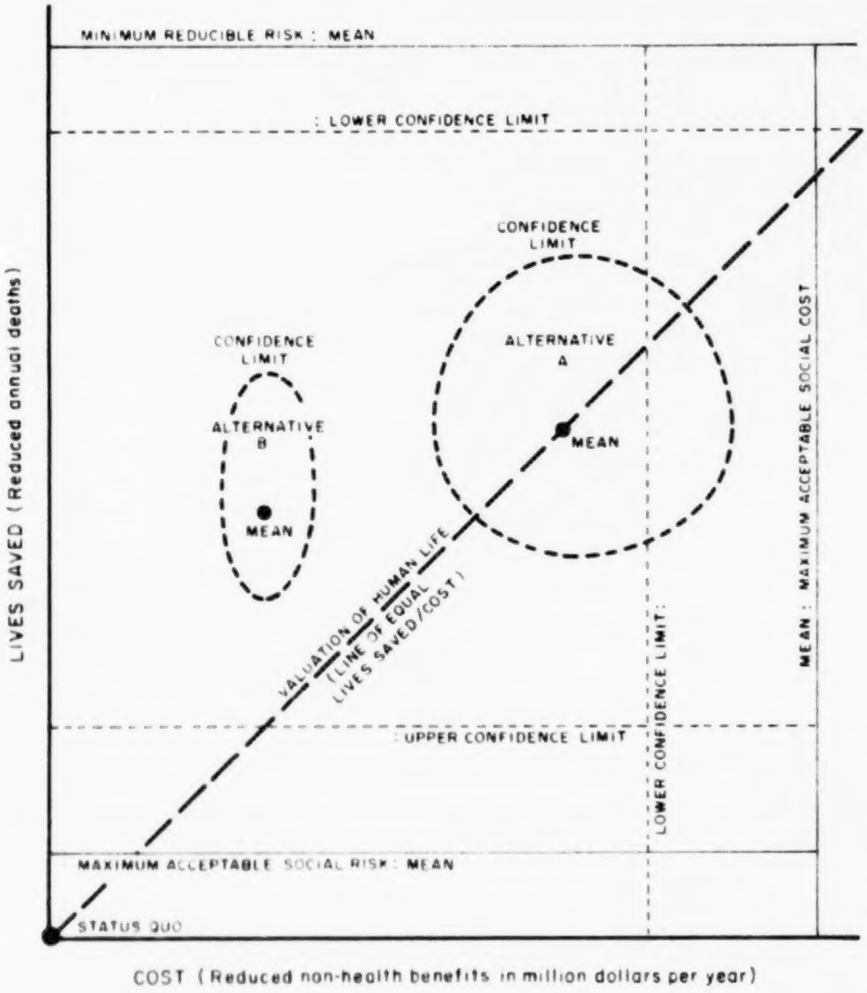
MINIMUM REDUCIBLE RISK : MEAN
: LOWER CONFIDENCE LIMIT
CONFIDENCE LIMIT
ALTERNATIVE A
MEAN
CONFIDENCE LIMIT
ALTERNATIVE B
MEAN
VALUATION OF HUMAN LIFE (LINE OF EQUAL LIVES SAVED/COST)
LIVES SAVED (Reduced annual deaths)
MEAN : MAXIMUM ACCEPTABLE SOCIAL COST
LOWER CONFIDENCE LIMIT :
: UPPER CONFIDENCE LIMIT
MAXIMUM ACCEPTABLE SOCIAL RISK : MEAN
STATUS QUO
COST (Reduced non-health benefits in million dollars per year)

FIGURE 8-2 MULTIPLE CRITERIA DISPLAY SAMPLE

and the effects of factors that have not even been considered will in general create much wider uncertainties than those of the computational approximations.

The confidence limits described here should not therefore be accepted as precise statistical evaluations. Rather, they are approximate estimates that attempt to show the first-order effects of combining the many uncertainties involved in chains of calculations leading to each decision criterion. Even this limited role is indispensable to formulating an improved criterion system for risk analysis. It is greatly superior to leaving uncertainty evaluation to human judgment. Humans are notoriously deficient in combining uncertainties subjectively, and they tend unless continually reminded of the presence of uncertainty to suppress its very existence.

Primary Trade-off Criteria

In the recommended multiple criteria approach, two considerations must dominate just as they do in the more conventional cost-benefit approach. In the proposed approach, the two incommensurable considerations are compared so that relationships between them can be shown without requiring that they be reduced to common terms. (Where two considerations can be reduced to common terms, they can be combined into one dimension.)

The two most significant considerations can vary depending on the nature of the problem, but at least one will nearly always be some measure of monetary value. In the cases examined in this study, this consideration is the net non-health economics benefit of an environmental control action. Since health effects are the major motive for environmental controls, the net non-health effects are most likely to be negative. (Such negative effects include higher prices and consequent lower production of the process being controlled, unemployment, unfavorable balance of trade shifts, and others discussed in Chapter 5.) Economic benefits in this context are therefore best thought of as reductions in benefits, and their graphical presentation is most conveniently expressed as negative changes from the existing status quo, which would be located at the origin as in Figure 8-2.

The second consideration, measuring some aspect of the risk, in this case is the effect of the control on human health. More precisely, it is the effect on death rate, which as with benefits would be expressed as a reduction (see Figure 8-2). Health effects can be expressed in terms of morbidity, days of disability, or even dollars spent for loss of work time and cost of medical care. However, these other effects are not explicitly evaluated here. For completeness in an overall economic analysis of such morbidity these effects might be considered, but as explained in Chapter 7, they will not significantly modify the methodology or conclusions of the type of analysis illustrated here.

Comparison of the alternatives is carried out graphically by picturing the relative changes in risks and benefits in two dimensions in Figure 8-2. Their risk/benefit ratios will then be a function of the slope of the lines connecting them to the origin and to each other. Additional criteria can also be considered, as explained below. Other types of considerations could be used instead of mortalities as measures of risk; for example, esthetics, comfort, recreational value, and ecological quality. However, they are unlikely to be as great a concern as human health and safety in the evaluation of hazardous wastes and would generally, if at all, be included in one of the supplementary considerations that are discussed below.

Other Criteria

Several considerations that are important to risk analysis from a behavioral (i.e., practical decision-making) standpoint can be included as constraints to the basic risk-benefit trade-off. These constraints will tend to limit the domain of feasible or acceptable solutions, so that certain otherwise desirable alternatives may be eliminated.

Cost Constraint--A practical constraint in many governmental programs is that of the cost of the program. If the costs are to be borne by the government, they are subject to rather strict overall budgetary limits.[81] Even if most of the costs are to be borne by industry or the public, their magnitude will be limited to the reluctance of legislators to impose sudden onerous new burdens. The tendency of public bodies to follow "incrementalism" in making policy applies here as in other fields. An example is the case of auto emission controls, which started modestly and have gradually grown to increasingly expensive equipment, with proportionately increasing counterpressures against further increases.

"Maximum Acceptable Social Cost" has not previously been applied formally as a limitation to risk-benefit trade-offs, and its specific limits are not at this time very well defined. However, its existence has been well documented in other budgetary fields, and it is likely to become more explicit in federal programs under the new Congressional budget limiting procedure. In the case of existing budgeted programs, short term (one year) incremental changes are likely to be limited to 10 percent or so of existing government environmental budgets in the absence of new authorizations. Long-term limits on acceptable costs are likely to be limited by more fundamental relationships such as how much society is willing to invest in analogous prudently oriented concerns as preventive medical care, public health, public safety, and defense. Uncertainties will apply to both short-term and long-term limits but they will be much greater for the long-term limits. An illustration of the type of constraint that Maximum Acceptable Social Cost considerations impose on the system is shown in a vertical Expected Value line in Figure 8-2, with a parallel Lower Confidence Limit to its left. In many situations the line would slope upward to the right to reflect the practical trade-offs that usually occur between cost and risk.

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[81] O. A. Davis, M.A.H. Dempster, and A. Wildavsky, "A Theory of the Budgetary Process," The American Political Science Review, p. 542+ (September 1966).

Maximum Acceptable Social Risk--A comparable and better documented constraint is that of "Maximum Acceptable Social Risk." This limit is based on various as-yet poorly understood factors, including the endemic disease rate, voluntary or involuntary nature of the risk, ratio of risks to benefits, and salience and degree of understanding of the risk. Chauncey Starr[a2] points out that while volunteer professional workers and amateur daredevils are willing to engage in activities up to a thousand times more dangerous than are other people, the general public seems unwilling to accept fatality rates from common activities that are significantly greater than those from disease.

Maximum Acceptable Social Risk as a concept can be made more specific by a Short-Term Maximum Acceptable Social Risk that reflects the current standards for any particular social hazard. Starr himself illustrates how risk standards tend to become stricter over time as usage and experience increase, as in the cases of automobile and air transportation. Chapter 2 of this report describes how particular environmental standards follow a similar time pattern in an "incremental" fashion. Analysis of the current pattern, the time-trend from previous standards, and analogous trends for comparable hazards should enable one to project likely future standards.

[a2] C. Starr, "Benefit-Cost Studies in Sociotechnical Systems," pp. 17-42 in "Perspectives on Benefit-Risk Decision Making," National Academy of Engineering (1972).

Logically, then, one could expect the feasible domain for risk standards to be limited both in the short-term by proximity to presently accepted standards and in the long-term by more fundamental relationships to the general disease level. An example of the short-term type of risk constraint, together with its lower confidence limit, is shown in Figure 8-2. (Location of the risk constraint above the status-quo level indicates that some reduction in present deaths is demanded. Its horizontal slope, like the vertical slope of the Maximum Acceptable Social Cost constraint, indicates a possible oversimplification because it neglects any cost/risk trade-offs.)

Minimum Reducible Risk--A "Minimum Reducible Risk" level represents a residual (i.e., background) absolute risk that remains after all feasible precautions have been adopted. This constraint can be particularly useful in some analyses because it can be fixed with reasonable precision and thereby it establishes a ceiling to the decision domain. A Minimum Reducible Risk limit is shown at the top of Figure 8-2.

Life Valuation--The problem of valuing human life remains an obdurate one in law, welfare economies, and risk-benefit analysis even though considerable progress has been made in recent years to resolve the theoretical issues. Mishan[23] maintains that such life-valuing methods as potential future earning power, net future value to society, social evaluation as reflected in political decisions, and incentives to purchase life insurance are all inadequate as measures. The most theoretically valid measure, according to the Pareto criterion of social welfare, is the worth to an individual of reducing his own risk of death as derived from his "revealed preference"[22] (see discussion in Chapter 7).

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[23] E. J. Mishan, "Economics for Social Decisions," Elements of Cost-Benefit Analysis (Praeger Publishers, New York, 1973).

Thaler and Rosen[84] have estimated this worth to American workers as about $200,000 in 1967 dollars. Melinek[85] estimates by similar methods that valuations by the general population in Britain are slightly lower: £50,000 or $120,000.

Many people object, however, to society itself establishing such a value, and so explicit valuation in government planning and standard setting has remained controversial. The methodology advocated here avoids explicit valuation because risk measurement is separated from measures of economics benefit. The two can be simply related however, by the angle of lines drawn between alternatives in Figure 8-2. For example, the slope of a line drawn from the status-quo point at the origin to any alternative (which equals the reduction in benefits ÷ the reduction in deaths) represents the implicit life valuation of that alternative. Such a line is drawn through Alternative B in the figure. If a decisionmaker chooses some alternative, he therefore can tell from this formulation what his implicit valuation of human life is. Conversely, if he values human life at not less than some particular amount, he can consider only alternatives that lie above that value line.

Risk Aversion--Almost all people except gamblers have an aversion toward risk; such aversion accounts for the popularity of the insurance industry. Several ways can be found to account for various aspects of risk aversion in the display graphs. Probably the best method (not shown here but discussed in the next chapter) involves decision procedures that discriminate against alternatives with the larger confidence rings, which imply greater uncertainties.

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[84] R. Thaler and S. Rosen, "The Value of Saving a Life: Evidence from the Labor Market," paper presented 30 November 1973; published by Univ. of Rochester.

[85] S. J. Melinek, "A Method of Evaluating Human Life for Economic Purposes," Fire Research Note No. 950, Herts., England (November 1972).

Distributional Comparisons

Trade-off comparisons between risks and benefits can only be calculated for one interest group at a time. The important distributional question of who within or beyond that one group takes the risks and who receives the benefits cannot be answered by that one trade-off comparison. To answer distributional questions, trade-off calculations would be made as feasible for each separate interest group of concern to the decisionmaker, so that comparisons can be made of differences among the trade-offs of different interest groups as shown in Figure 8-1(C).

Conventionally in studies of national environmental standards, risk-benefit comparisons are made for the nation as a whole. To allow for distributional considerations, many other risk-benefit comparisons might be made for such special groups as:

- Local hazardous waste producing areas.
- Local areas nearby but not part of the producing areas.
- Local or regional areas with consumer rather than producer interests.
- Future populations of producing or consuming areas.
- Specialized occupational groups and their families.
- Special-interest affiliations such as income classes or ethnic groups.

Supplementary Criteria

Some criteria simply cannot be integrated with others in any formal way. Nevertheless, they should be arranged together as proposed by Abel[86] and illustrated in Figure 8-1(D) so that the decisionmaker will be able to consider all major factors in one group. In a formal procedure such as standard-setting, where administrative and judicial review are always possible if not probable, it is important to make as all-inclusive a listing of this type as possible, so that interested parties will be able to see that considerations considered relevant by them have in fact been included in the evaluation process.

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[86] F. H. Abel and D. P. Tihansky, "Methods and Problems of Estimating Water-Quality Benefits," Amer. Water Works Assn. J., Vol. 66, No. 5, pp. 276-81 (1974).

Cadmium Examples

Presentation of results will depend on the hazardous waste, the decisionmaker, the decision process, the type of situation to be decided, and other factors. However, the general process can be followed through for specific emission control alternatives to illustrate the kinds of information and presentations that can be anticipated. Since in our present examples, we only have one alternative that meets the control problem, we will compare the distributional aspects of that alternative in our presentations. Risk-benefit trade-offs and other considerations will be compared in each problem for the nation as a whole versus the local producing areas.

Zinc Smelter Scrubbers

Among the examples studied for this report, the most interesting and significant is perhaps that of limestone scrubbers as applied to cadmium emissions by zinc smelters. For the risk variables, Chapter 7 reports that about 166 person-years can be saved by cadmium reductions in the first year after imposition of scrubber controls on the nation's zinc smelters. Reference to the confidence limits of Figure 7-3 indicates that the saving might range between about 100 and about 360 person-years per year of controls. Lives saved are those of people residing near the smelters (within 30 kilmeters), so the risk reduction in the local producing areas is essentially the same as for the nation as a whole. The major difference is that population mobility is so great that the local area will not have to continue to be responsible for most of the people now being exposed because they will have moved. but the federal government will still in most cases have to be concerned. This difference is not considered here.

The most significant direct national cost resulting from the new controls and their effects on zinc prices are a loss of Gross National Product: $21 million per year (from Table 5-2). Although the local zinc-producing areas contain only one percent of the U.S. population, the local economic losses are two-thirds as high as the total national loss, $14 million, because they include local multiplier effects that cancel out at the national level. Confidence limits for both national and local losses are estimated as multiplier and divisor factors of 1.7. A graphic illustration of these trade-offs is shown in Figure 8-3.

Among the other possible considerations, no Maximum Acceptable Social Cost was identified because to do anything at all would require initiation of a new national program, but the cost magnitudes envisaged do not appear to present any overriding difficulties to federal financing. The Minimum Reducible Risk also cannot be related to this chart because no simple procedure can be applied to both national and local total lives saved.

However, the World Health Organization recommended value of Maximum Acceptable Social Risk of 60 μg/day (mentioned in Chapter 2) could place a severe constraint on the acceptable domain of cadmium controls. To simplify calculations for an approximate estimate of this constraint, we first must subtract the average 50 μg/day average ingestion from food and water. The margin for contributions from other sources then averages only 10 μg/day, which is equivalent to 60 ng/m^3 continuous exposure in air. Figure 6-2 shows that 60 ng/m^3 is only one-fifteenth the current maximum exposure from smelters, so not more than about one-fifteenth the current deaths from smelter emissions should be allowable under this standard.

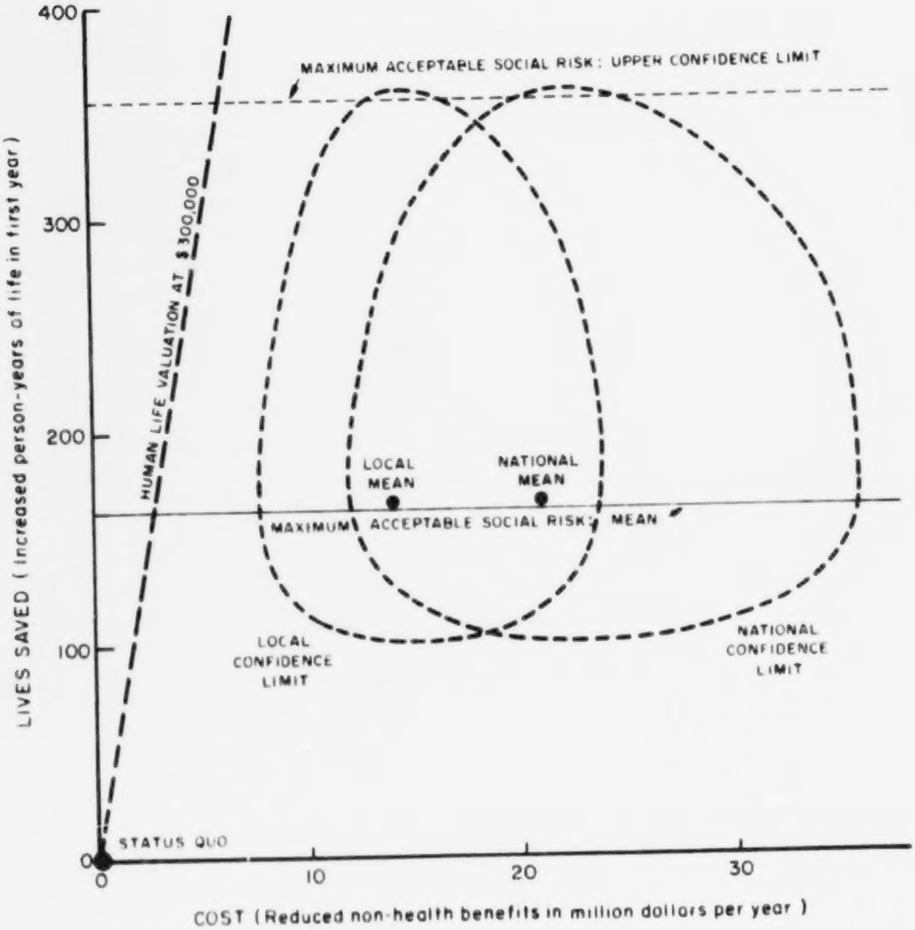

FIGURE 8-3. CADMIUM RISK BENEFIT COMPARISON-- LOCAL AND NATIONAL SMELTER SCRUBBER CRITERIA

Therefore, the mean value of lives saved under the WHO standard should be about 14/15^{ths} of the lives saved by perfect smelter controls. Since the proposed controls that save 166 persons-years are only 95 percent perfect, the required mean savings under the controls is 166 x 14/15 ÷ 95% = 163 person-years. The upper confidence limit is applied in the same way to the maximum expected lives saved by smelter controls to equal 354 person-years. These limits, shown in Figure 8-3, indicate that the proposed scrubbers are only minimally effective in meeting the WHO standards.

Another criterion that can be illustrated in Figure 8-3 implies a contradictory conclusion. If a Valuation of Human Life analysis is desired the "Lives Saved" vertical scale must be converted from person-years to actual lives. For 50-year-olds with a life expectancy of 20 years, the ratio is 20 person-years to one life. But most life valuations are based on an average population, which for calculating we assume average 35 years old with a life expectancy of 35 years. They expect 35 person-years per life. If we inflate the aforementioned average 1967 life value of $200,000 to $300,000, the value per person-year will then be $8,700. The value of 166 person-years will only be $1.45 million, which is barely one-tenth the local cost of the smelter scrubbers and an even smaller fraction of the national cost. Scrubbers, therefore, do not appear cost-effective in protecting against cadmium. (Their effectiveness against other contaminants such as heavy metals, SO_2, and arsenic is not estimated here although it is obviously relevant to overall scrubber values.)

Finally, the kind of supplementary criteria that cannot be integrated into the chart can be gathered together with the above criteria in the manner described for Figure 8-1(D). This type of information for the case of a potential cadmium smelter control is shown in Figure 8-4. Note that this formulation provides a slightly different perspective to the type of data shown in Figure 8-3, and in addition relates the

CRITERION	QUANTITY OR QUALITY		CONDITIONS AND QUALIFICATIONS
	STATUS QUO	SCRUBBERS	
RISKS			
LOST PERSON-YEARS	175	9	SCRUBBER EFFECTIVENESS 95%
LOST DISABILITY-YEARS	?	?	NOT ANALYZED
POPULATION EXPOSED	2 MILLION/YR	2 MILLION/YR	MOBILITY MODEL IMPLIES 7.8% = 156,000 NEW EXPOSURES PER YEAR
No. ACTUAL LIVES LOST	30	6	ESTIMATE FROM EXPOSURE, DOSE-DAMAGE, AND POP. MOBILITY MODELS
YEARS LOST/PERSON	6	1½	BASED ON 50 YEAR-OLD LIFE EXP.
EQUIV. "AVERAGE" LIVES LOST	5	¼	"AVERAGE" LIFE EXPECTANCY = 35 YEARS
VALUE OF LIVES LOST	$1.5 MILLION	$75,000	VALUATION AT $300,000/AVERAGE LIFE
DISABILITY LOSSES	?	?	NOT ANALYZED
MEDICAL CARE COSTS	?	?	NOT ANALYZED
BENEFITS			
EFFECT ON CONSUMER SURPLUS	0	-$14 MILLION/YR	SEE TABLE 5-1
EFFECT ON WAGES	0	-$10 MILLION/YR	SEE TABLE 5-2
EFFECT ON PRODUCTION	0	-$21 MILLION/YR	"
EFFECT ON DOMESTIC PROFITS	0	-$19 MILLION/YR	"
EFFECT ON TAXES	0	-$10 MILLION/YR	"
EFFECT ON INVESTMENT FUNDS	0	-$9 MILLION/YR	"
EFFECT ON TRADE BALANCE	0	-$28 MILLION/YR	"
EFFECT ON PROPERTY VALUES	?	?	NOT ANALYZED
ENVIRONMENTAL EFFECTS			
VEGETATION LOSSES	SOME	REDUCED	REF. FULKERSON CHAP. VI
ANIMAL LOSSES	?	?	"
CONCENTRATION IN BIOSPHERE	SOME	REDUCED	SEE CHAP. 6
FOOD LOSSES	SOME	REDUCED	POSSIBLE EXCESSIVE LEVELS IN CROPS
MATERIAL DAMAGE	-	-	NO EVIDENCE CITED
AESTHETICS	-	-	DIRECT EFFECT INSIGNIFICANT
RECREATION	SOME	REDUCED	MINOR EFFECT ON FISHING POSSIBLE

FIGURE 8-4 CADMIUM RISK-BENEFIT DISPLAY SUPPLEMENTARY CRITERIA FOR SMELTER SCRUBBERS

quantitative data to additional information of a qualitative or incommensurable quantitative nature that otherwise might be lost to the evaluation.

Municipal Incinerators

Cadmium emissions from municipal incinerators are much less hazardous than those from smelters, because the concentrations around individual sources are much lower. While the expected life-saving from cadmium reductions by scrubbers in zinc smelters has been calculated in Chapter 7 at 166 person-years, the savings by scrubbers in municipal incinerators are less than one person-year. At the same time, the loss in non-health benefits from installing scrubbers in municipal incinerators ($28 million nationally) is almost twice the loss from smelter scrubbers, because the number of units that would have to be installed is much greater.

Considering the uncertainty ranges in both risks and benefits, the overall range of the implicit valuation of human life is quite wide, as shown in Table 8-1. However, the valuation even under the lowest assumptions is so high as to be prohibitive if reduction of cadmium emissions were the only incentive. Because of this constraint to feasibility, and the analytic similarity to the zinc scrubber alternative, municipal incinerator controls are not examined in further detail here.

Asbestos Examples

Graphical comparisons of asbestos control risks and benefits were not drawn because the lack of any discernible fatality effects at the dose rates derived from our emissions model rendered any two-dimensional comparison useless. The lack of observable health effects from the model seems due to the assumption that all exposure would result from contaminants dispersed over a wide area, as from a plant stack or from brake dust. It is certainly interesting to find that these types of exposures from asbestos seem inconsequential. Their benign levels indicate that perhaps environmental controls over asbestos eimssions from industrial

Table 8-1

IMPLICIT VALUATION OF HUMAN LIFE BY REDUCING CADMIUM EMISSIONS WITH STACK SCRUBBERS IN MUNICIPAL INCINERATORS

National Economic Costs		Lives Saved		
		Upper Confidence Interval 0.03 Life	Mean 0.003 Life	Lower Confidence Interval 0.0003 Life
Lower confidence interval	$23 million	$800 million	$8 billion	$80 billion
Mean	$28 million	$900 million	$9 billion	$90 billion
Upper confidence interval	$34 million	$1.1 billion	$11 billion	$110 billion

and automobile brake sources can be minimized. However, another and undoubtedly more hazardous source of asbestos inhalation--direct handling of the material itself or intimate exposure to activities where it is being worked--has not been analyzed here.

Asbestos Industry

Since Chapter 7 shows zero risk reduction from adoption of emission controls in the asbestos industry, the implicit valuation of human life derived by calculating the benefit-risk ratio for asbestos industry controls must approach infinity. This is clearly not a very feasible criterion for risk reduction. Nevertheless, detailed examination of the economic costs of asbestos industry controls does show one interesting phenomenon. As discussed in Chapter 5, national economic effects of a control program would be a loss of about $2.9 million in the form of reduced consumer surplus, as control costs were passed on to the consumers. But the loss of consumer surplus would only be about $29,000 in asbestos producer areas (one percent of the national loss), and industry owners would not lose anything because they could pass their costs along. The major effect in producer areas would be a gain of perhaps $400,000 from the addition of about 40 workers associated with operation and maintenance of the control equipment.

In this situation, the most rational motivation in asbestos-producing areas for an asbestos control program would most likely be from the financial and employment (not the health) self-interest of the local labor force.

Elimination of Asbestos Brake Lining

The hypothetical example of replacing asbestos brake linings with an undefined material of equal performance but 50 percent more expensive yields more consistency between costs in the asbestos producer area and those in the country as a whole. In the case of brakes, national costs of imposing a 50-percent higher price for linings are dominated by a $65 million loss in consumer surplus. Losses in local asbestos-producing areas are less than one-twentieth this amount even though significant local multiplier effects can be assumed. Overall, the non-health economic effects would be consistently negative everywhere except in locations where the replacement brake lining material is produced. From an environmental standpoint, elimination of asbestos brake linings appears useless for the same reason that imposing asbestos emission controls do--the number of lives to be saved is significant. At the same time, however, strict exposure control over close contact with asbestos by brake repairmen, asbestos miners, fabricators, and construction personnel seems from empirical evidence to be clearly needed. But the exposure model needed for that analysis must be based on the specific work activities engaged in rather than on the general emission and dispersion parameters used in this study.

Chapter 9

METHODS FOR DETERMINING ACCEPTABLE RISKS AND ASSOCIATED RESEARCH NEEDS

Practical Considerations

Even after decision data have been formulated and compared in the manner of Chapter 8, several alternatives might remain competitive. In addition, further alternatives can generally be found by enlarging the scope of decisions to include future policies, research and development programs, and other choices that are relevant but not directly tied to the current alternatives. This chapter provides some clues, but no final answers, for how such choices can be made from the compiled data.

One major reason why no final answers can be given is the same as that presented in Chapter 8: no program can reasonably expect to anticipate all of the considerations affecting the decision-maker. Actually, the difficulty is even more fundamental than just attempting to anticipate one decision-maker. In the operations of a democratic government, decisions-makers are ultimately responsible to all of the people. Yet the work of the economist Kenneth Arrow has proved that, in general, there is no single optimum democratic social choice.[87]

All social choices must be made on the basis of individual values that represent an imperfect compromise for society at large. When one accepts the compromises as described in Chapter 8, then the remaining need is to assist the decision-maker in his choice. This can be complicated because, in many cases, the multiple criteria will conflict with each other.

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[87] E. T. Haefele, Representative Government and Environmental Management, p. 17 (Johns Hopkins Press for Resources for the Future, Inc., Baltimore, 1973).

Any general decision method must be compatible with the decision-maker's own procedures and his own anticipations of the outcome of his decision. The method, in other words, must fit with such characteristics as the "incremental" characteristic of decision-making that was described in Chapter 8. For example, the types of small moves away from the existing situation that are followed in incremental decision-making can be visualized very well in the two-dimensional graph of Figure 8-2, where the status quo situation is placed at the origin. By that presentation, alternatives located closest to the origin are easily seen to require the least incremental movement and, therefore, may be preferred to alternatives farther away.

Related to incrementalism is feedback--another policy-maker's characteristic in a list compiled by Lindblom.[88] Feedback in government was first described in considerable detail from a cybernetic standpoint by Karl Deutsch.[89] It is the process of constant adjustment and correction when a policy is put into practice, as reflected in the philosophy of "Never time to do it right--always time to do it over." In practice, it is the information process that accompanies and expedites "sequential" decision-making--another characteristic often mentioned. Short-sighted feedback and rapid sequential decisions are usually deplored by those whose orientation is toward planning or standardization, but they are dominant behavioral characteristics of most operating organizations.

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[88] C. E. Lindblom, The Policy-Making Process, p. 24+ (Prentice Hall, Englewood Cliffs, N. J., 1968).

[89] K. W. Deutsch, The Nerves of Government (The Free Press, N. Y., 1965).

The graph of Figure 8-2 is designed in two ways to emphasize the importance of information feedback. First, its cost and risk information is in annual terms--partly for the reason that new planning information or economic developments could change the trade-offs significantly. Second, the confidence limits reflecting uncertainties will change over time as information is obtained, so the decision conditions as drawn will usually be valid at only one time.

So many information inputs, in fact, require feedback to refine their information that almost any first attempt at integrating data, including this study, can be significantly improved by subsequent analysis. Among the kinds of information feedback needs that have not been available to this study are:

- Resolution of uncertainties by the adversary process of searching for better information to support ones' case. This process is achieved in the normal course of EPA standards hearings.
- Estimation of the interactive effects of multiple factors on the environment. For example, no consideration has been given to the potential benefits of smelter controls in reducing arsenic pollution. (Arsenic has recently been named by the National Cancer Institute as the prime suspected cause of elevated lung cancer rates around smelters.)
- Discovery of unknown factors that more thorough search and future research efforts may find.
- Resolution of conflicting constraints on the feasible domain of alternative solutions. As has been noted, constraints in many cases have to be adjusted to each other as well as to social and economic influences.

Another typical characteristic of organizational decision-making, first described by Herbert Simon,[2] is "satisficing." (He invented the term "satisfice" as as combination of satisfy and suffice.) According to this criterion, the decision-maker does not attempt to maximize any particular criterion but rather seeks minimum satisfactory levels for all of the criteria important to him. Again, the presentation of Figure 8-2 is well adapted to this characteristic because it provides a decision domain within which all the pictured criteria are at or above minimum required levels. Any alternative lying within the decision domain by definition offers a "satisficing" solution.

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[2] H. A. Simon, Administrative Behavior: A Study of Decision-Making Processed in Administrative Organization, p. xxxv (MacMillan, New York, 1957).

Closely related to "satisficing" is the emphasis on "bottlenecks" in policy-making. The most attention in organizations is given to the most apparent bottleneck preventing a "satisficing" solution. Figure 8-2 highlights the most obvious bottlenecks by picturing those constraints that are not satisfied by the solution.

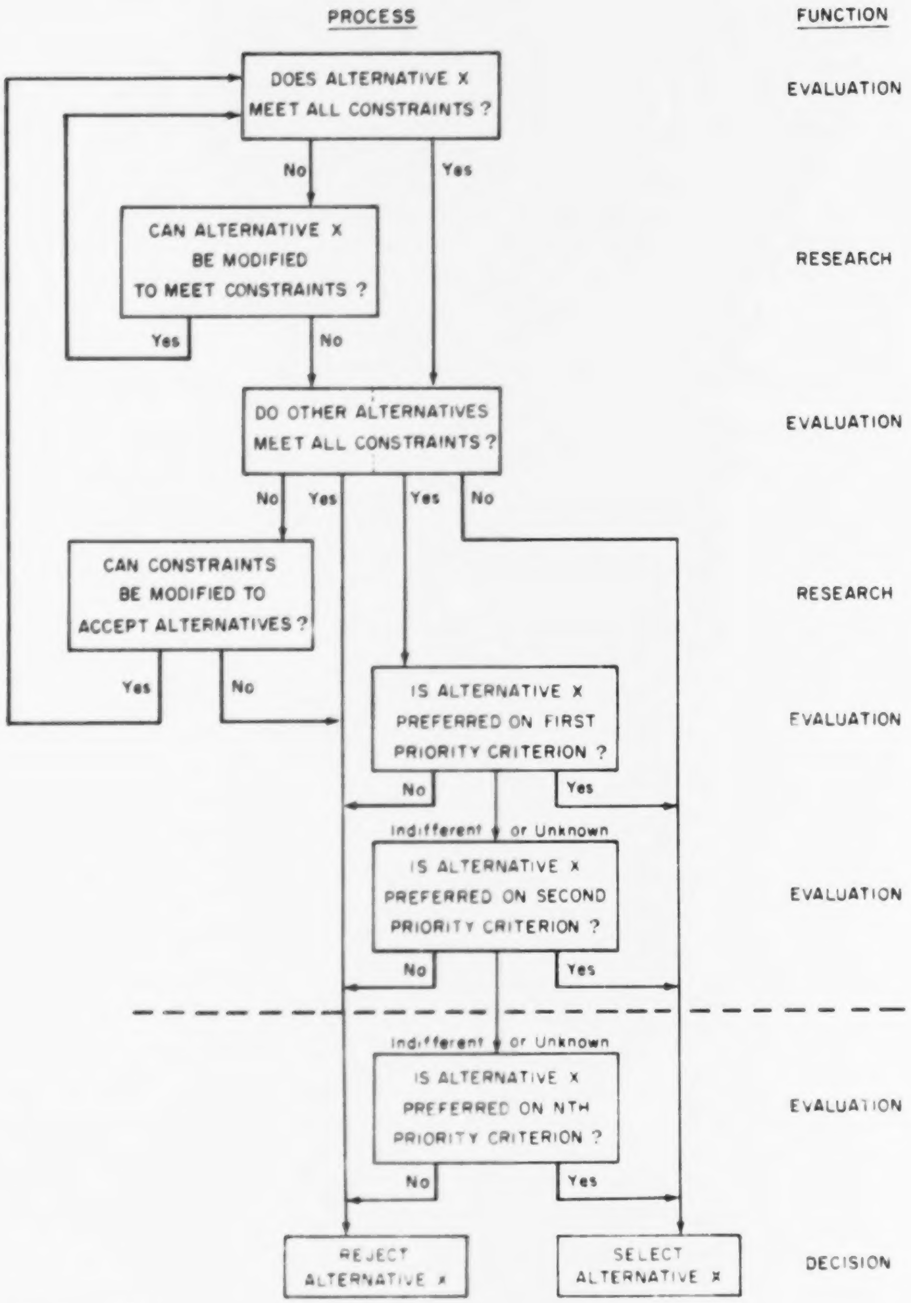
Methods for Choosing Control Alternatives

This focus on "bottlenecks" is an important step in the multiple criteria decision method discussed in Chapter 8. Any criterion that an alternative does not fulfill to some "satisficing" level serves as a bottleneck that prevents the solution of that alternative. Only those alternatives that have no serious bottlenecks are acceptable for solution as control policies.

Once the alternatives that meet the constraints have been identified, the next analytical step is to find the best of the acceptable alternatives. Only when both steps have been accomplished will it be possible to recommend a choice to the decision-maker.

Selection Procedure

The flow of decision data leading to the choice of a preferred alternative is shown in Figure 9-1. Note that the flow requires both the functions of evaluation and research, operating in an iterative feedback fashion, to reach the final decision. In this section we are interested


PROCESS
FUNCTION
DOES ALTERNATIVE X MEET ALL CONSTRAINTS ?
EVALUATION
No
Yes
CAN ALTERNATIVE X BE MODIFIED TO MEET CONSTRAINTS ?
RESEARCH
Yes
No
DO OTHER ALTERNATIVES MEET ALL CONSTRAINTS ?
EVALUATION
No
Yes
Yes
No
CAN CONSTRAINTS BE MODIFIED TO ACCEPT ALTERNATIVES ?
RESEARCH
Yes
No
IS ALTERNATIVE X PREFERRED ON FIRST PRIORITY CRITERION ?
EVALUATION
No
Yes
Indifferent or Unknown
IS ALTERNATIVE X PREFERRED ON SECOND PRIORITY CRITERION ?
EVALUATION
No
Yes
Indifferent or Unknown
IS ALTERNATIVE X PREFERRED ON NTH PRIORITY CRITERION ?
EVALUATION
No
Yes
REJECT ALTERNATIVE X
SELECT ALTERNATIVE X
DECISION

SOURCE SRI

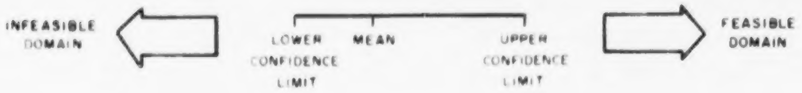
FIGURE 9-1 DECISION FLOW SCHEMATIC FOR SELECTION OF ALTERNATIVE CONTROLS

in evaluation methods rather than research, so we will start by discussing how to carry out the first, third, and fifth steps.

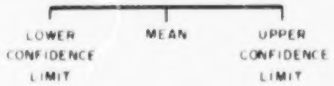
Evaluating the first step, "Does alternative X meet all the constraints " depends on how one defines the feasible domain and treats the uncertainties. Figure 8-2 shows uncertainties in both the alternative and the constraint values; in general the border between the feasible domain and the infeasible will be fuzzy rather than a single sharp line. These uncertainties can be retained as a probability distribution in subsequent steps of the analysis, but it is usually easier to decide on some cutoff assumption as the basis for evaluation.

Several approaches to the problem are shown in Figure 9-2, where the formal probability model and the three most well-accepted rule of thumb principles for dealing with uncertainty are illustrated. Figure 9-2(A) shows the horizontal placement of a hypothetical left border line of the feasible domain of a graph such as the one described above in Figure 8-2. The uncertain location of the line is represented by the uncertainty band extending from the lower confidence limit at the left through the mean value to the upper confidence limit at the right. (For consistency with the preceding chapters, we assume that the true boundary of the feasible domain lies to the left of the lower confidence limit with only 2.5 percent probability, to the left of the mean with 50 percent probability, and to the left of the upper confidence limit with 97.5 percent probability.) Figure 9-2(B) is a similar graph showing the uncertainty band for the horizontal location of alternative control X. The joint probability that the border lies to the left and alternative X lies to the right of any given location is shown by means of a probability density diagram in Figure 9-2(C). If the probability densities are converted to cumulative probabilities as in Figure 9-2(D), the maximum cumulative probability can be read as the overall probability that alternative X will lie in the feasible domain. The analyst can then apply this

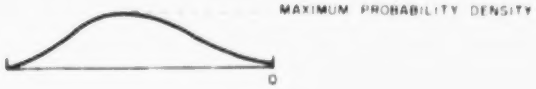
(A) LOCATION OF VERTICAL LEFT-HAND BORDER OF FEASIBLE DOMAIN


INFEASIBLE DOMAIN
LOWER CONFIDENCE LIMIT
MEAN
UPPER CONFIDENCE LIMIT
FEASIBLE DOMAIN

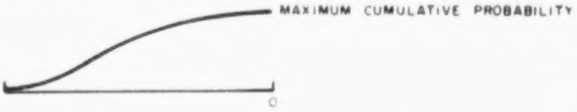
(B) HORIZONTAL LOCATION OF ALTERNATIVE X


LOWER CONFIDENCE LIMIT
MEAN
UPPER CONFIDENCE LIMIT

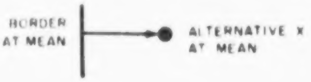
(C) PROBABILITY OF BORDER LEFT AND ALTERNATIVE RIGHT OF GIVEN LOCATION



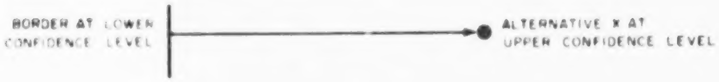
(D) CUMULATIVE PROBABILITY OF BORDER LYING TO LEFT OF ALTERNATIVE X



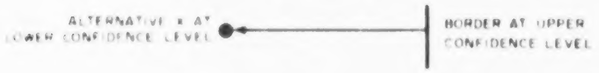
(E) ESTIMATED LOCATION BY "EXPECTED VALUE" DECISION PRINCIPLE


BORDER AT MEAN
ALTERNATIVE X AT MEAN

(F) ESTIMATED LOCATION BY "OPTIMISM" PRINCIPLE


BORDER AT LOWER CONFIDENCE LEVEL
ALTERNATIVE X AT UPPER CONFIDENCE LEVEL

(G) ESTIMATED LOCATION OF "PESSIMISM" PRINCIPLE


ALTERNATIVE X AT LOWER CONFIDENCE LEVEL
BORDER AT UPPER CONFIDENCE LEVEL

SOURCE: SRI

FIGURE 9-2 EXAMPLE ESTIMATES OF LOCATION OF ALTERNATIVE CONTROL X RELATIVE TO FEASIBLE DOMAIN BORDER

overall probability to further statistical calculations, or he can compare it to some arbitrary criterion (such as 50 percent) to decide whether the first step in the decision process should be answered Yes or No.

If the decision problem is neatly specified in terms of probability distributions, the cumulative probability approach will yield the most exact and elegant answers. However, if the distributions are poorly defined, as has been the case in most of the confidence intervals examined in this study, then more approximate rules of thumb may provide decision rules that are adequate to the level of accuracy of the data.

Perhaps the simplest principle that could be used directly from limited data is the "expected value" comparison shown in Figure 9-2(D). In that figure, alternative X is accepted within the feasible domain by comparing its mean location with the mean location of the domain border and observing that alternative X lies to the right of the border. This method has the advantage of providing answers that will agree with answers based on acceptance of probabilities over 50 percent that have been estimated by formal probability calculations.

Other answers that deviate from the 50-percent criterion could be obtained from the "optimism-pessimism" principle.[21] Under that principle, decisions can be made on the basis of whether one assumes the best of all possible outcomes, the worst of all possible outcomes, or some outcome intermediate in the scale. Figure 9-2(F) is based on the "optimism" criterion; it compares locations under the most favorable outcomes of the domain border at its lower confidence limit and alternative X at its upper confidence limit. By this criterion, alternative X would be located well inside the feasible domain. Figure 9-2(G), in contrast, is based on the "pessimism" criterion; it shows alternative X far outside the feasible domain border under the worst outcomes of both variables. Optimism and pessimism criteria permit biases to be systematically introduced to the expected value estimates; they also provide a simple means of conducting sensitivity analyses of the uncertainties.

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[21] R. D. Luce and H. Raiffa, Games and Decisions, p. 282 (Wiley, N.Y., 1957).

One final principle not shown in Figure 9-2 is that of "regret." Regret has the objective of minimizing the regret that one could suffer if the outcome of his chosen decision was most unfavorable. (The potential regret of choosing the expected value principle in Figure 9-2(E), for example, is the sum of the differences between the mean and the most unfavorable confidence limit: the mean-to-lower-confidence-limit distance of alternative A plus the mean-to-upper-confidence-limit distance of the border.) Regret, in other words, is a principle of limiting uncertainties--the most favorable choice under regret is the one with the least range of uncertainty. Government officials and other risk-averse decision-makers might see considerable virtue in such a principle. It could be used with one of the other principles to identify alternatives that are both acceptable and reliable. By itself, however, regret gives no consideration to the expected value of an outcome, so it could dictate a choice that is generally inefficient or otherwise undesirable. Because of this characteristic, Kenneth Boulding has referred to the use of regret criteria as a sign of mental ill-health.

To again summarize the alternative selection procedures, the cumulative probability, expected value, optimism, pessimism, or regret principles or various combinations and variations, might each be most suitable under certain conditions. Each can resolve the first step in Figure 9-1 by determining whether alternative X is located in the feasible domain. They can answer the third step, "Do other alternatives meet all constraints?", in exactly the same way. But because they deal only with whether the alternatives satisfy all estimates and not with how to rank the alternatives, they cannot answer the fifth step: "Is alternative X preferred on the first priority criterion?"

Ranking Procedures

Preferences among the alternatives may be less important to establish than conventional economic theory would indicate, because the number and severity of constraints imposed by the multiple criteria are likely to greatly restrict the number of acceptable alternatives in practical situations. The pure "satisficing" model of choice is more realistic than the pure "optimizing" one. Nevertheless, any decision methodology should be able to establish preferences among alternatives.

Our approach recommends six different possible decision measures that can establish preferences among the five different decision principles shown in Figure 9-3. The five principles are the same as those discussed above, but here they are used for ranking rather than classification purposes. The six measures are optional criteria that might be used as ranking measures for alternative controls.

"Risk level," the first decision measure, is the one implicitly adopted when contaminant concentrations or exposure levels are set at the lowest possible levels achievable by any control method. Each of the principles operates on the risk measure in a slightly different way from the others, but they all attempt to select the alternative with the lowest overall risk.

"Net benefit" in effect is a negative measure of the overall cost of the control program. Maximizing the benefit is the same as minimizing the cost. This would be the measure to base decisions on if cost were the only measure of merit of a control program. But cost will seldom

DECISION PRINCIPLES / DECISION MEASURES	PROBABILITY	EXPECTED VALUE	OPTIMISM	PESSIMISM	REGRET
RISK LEVEL (R) (HEALTH EFFECTS)	MINIMIZE $\int p(R)R\,dR$	MINIMIZE MEAN OF R	MINIMIZE LCL* OF R	MINIMIZE UCL+ OF R	MINIMIZE UCL LESS ESTIMATED RISK
NET BENEFIT (B) (NON-HEALTH ECONOMIC EFFECTS)	MAXIMIZE $\int p(B)B\,dB$	MAXIMIZE MEAN OF B	MAXIMIZE UCL OF B	MAXIMIZE LCL OF B	MINIMIZE ESTIMATED BENEFIT LESS LCL OF B
BENEFIT/RISK (TOTAL BENEFIT-RISK RATIO)	MAXIMIZE $\iint p(B)p(\frac{1}{R})\frac{B}{R}dB\,d(\frac{1}{R})$	MAXIMIZE $\frac{\text{MEAN OF B}}{\text{MEAN OF R}}$	MAXIMIZE $\frac{\text{UCL OF B}}{\text{LCL OF R}}$	MAXIMIZE $\frac{\text{LCL OF B}}{\text{UCL OF R}}$	MINIMIZE ESTIMATED BENEFIT LESS PESSIMISM VALUE
ΔBENEFIT/ΔRISK (INCREMENTAL BENEFIT-RISK EFFECT)	MAXIMIZE $\iint p(\Delta B)p(\frac{1}{\Delta R})\frac{\Delta B}{\Delta R}d\Delta B\,d(\frac{1}{R})$	MAXIMIZE $\frac{\text{MEAN OF } \Delta B}{\text{MEAN OF } \Delta R}$	MAXIMIZE $\frac{\text{UCL OF } \Delta B}{\text{LCL OF } \Delta R}$	MAXIMIZE $\frac{\text{LCL OF } \Delta B}{\text{UCL OF } \Delta R}$	MINIMIZE ESTIMATED ΔB LESS PESSIMISM VALUE
BENEFIT LESS RISK (BENEFIT-RISK DIFFERENCE IN COMMENSURABLE TERMS)	MAXIMIZE $\iint p(B-R)(B-R)d(B-R)$	MAXIMIZE MEAN OF B LESS MEAN OF R	MAXIMIZE UCL OF B LESS LCL OF R	MAXIMIZE LCL OF B LESS UCL OF R	MINIMIZE ESTIMATED B-R LESS PESSIMISTIC B-R
PROBABILITY OF ALTERNATIVE LYING WITHIN FEASIBLE DOMAIN	MAXIMIZE $\iint_{\Omega} p(B)p(\frac{1}{R})\,dB\,dR$	MAXIMIZE PROBABILITY OF MEAN LYING WITHIN FEASIBILITY DOMAIN	MAXIMIZE FRACTION OF CONFIDENCE INTERVAL AREA IN FEASIBLE DOMAIN	MINIMIZE FRACTION OF CONFIDENCE INTERVAL OUTSIDE FEASIBLE DOMAIN	N/A

* LOWER CONFIDENCE LIMIT + UPPER CONFIDENCE LIMIT

SOURCE: SRI

FIGURE 9-3 POSSIBLE RULES FOR RANKING AMONG ALTERNATIVES

if ever be the only measure, since the very concept of controls introduces another measure (risk or environmental quality) that overrides cost considerations.

The absolute "benefit-risk" ratio is a more meaningful measure for the reasons discussed in Chapters 2 and 8. It suffers from being too comprehensive, however. In many cases it cannot be measured as an absolute value, and even where it can be measured it may not serve as the best indicator of the value of a particular alternative. "Change in benefit/change in risk" yields a more precise estimate of the effects of individual alternatives and it is easier to measure. It best fits the practical needs of incremental decision-making because it orients the analysis around the controllable effects of the alternative.

"Benefit less risk" difference also gives an incremental measure, but in general this type is less useful than the ratio. It requires that benefit and risk be presented in monetary or other commensurate terms, so it must violate the desirable trait of separating these two dimensions. It also is expressed in absolute terms, so it is insensitive to differences in the scale of different alternatives. However, in some circumstances it may be more understandable because it deals with actual values rather than with ratios.

Finally, the "probability of alternative lying within the feasible domain" is a different type of measure of merit, based on the fit of the alternatives within the constraints posed by all of the criteria in the problem instead of on measurements in only one or two criteria. This measure is of great value where the feasible domain is small relative to the scatter and uncertainties of the alternatives on the major dimensions of the problem. Such conditions seem quite common in the examples examined in this report, so this measure may prove to be more prominent in future studies than it has in the past.

Overall, however, the "change in benefit/change in risk" measure seems to be the most generally applicable of the six decision measures for the types of hazardous waste problems examined in this report. The large uncertainties involved in almost all of the data imply that expected value is probably the most practical of the decision principles to apply to this measure. But whichever techniques are used, the methodology suggested here can yield quantitative evaluations that lead, first, to solution of alternatives to meet the basic constraints of the environment, and second, to ranking of one preferred alternative from among all the "satisficing" alternatives. From this final ranking the final decision can be made as shown in Figure 9-1.

Methods for Analyzing Research Needs

The only steps in Figure 9-1 that have not yet been discussed are the two relating to research functions. These steps require the gathering of information by research, experimental, and monitoring groups who normally are not a direct part of the decision process but whose results are important to it. Since research results and other technical information are so essential to the decision process, their own decisions about the kinds of environmental information that are needed can have a great influence on the quality of research policy decisions. For these reasons, research and information-gathering decisions should properly be considered as part of the larger decision system. We will discuss these relationships in this section, and present a few hints about how they can be improved. At the same time, we do not attempt to present a comprehensive methodology on how to allocate research and development efforts or measure their benefits. Reviews of the extensive literature in this field suggest that such attempts have been, at best, only partially successful, and that some fundamental aspects of the R&D process remain unknown.[25] Neither do we intend to resort to the standard complaint that more research is needed. Perhaps the complaint is even more justified here than in other branches of knowledge, but from a practical standpoint, changes in the amount of research may not improve policy decisions so much as changes in the kinds of results that are being reported.

One clear finding of this study has been that most research results have given inadequate attention to uncertainties, and to how these uncertainties relate to those of other research studies with similar problems. Practically no attention has been given to summarizing the results in terms of the next higher level of generalization, so that the significance and relevance of the study could be more easily interpreted by readers. For example, data on animal experiments need to be related to applicability to human effects before the data can be usefully applied by studies such as the present one.

In attempting to integrate primary source materials, secondary studies discover the missing links between existing results as well as the inadequacies of the primary results themselves. In our survey, we have observed certain general needs for hazardous waste standard setting that seem typical of the types of information that are available. These needs and specific recommendations about them are shown in Table 9-1. They indicate that a whole new category of quantitative models is needed to use with risk-benefit and other trade-off studies. The models must be simpler than existing research models with less dependence on immediate local factors, but sensitive to variations in long-term environmental parameters.

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[25] N. Baker and J. Freeland, "Recent Advances in R&D Benefit Measurement and Project Selection Methods," Management Science, Vol. 21, No. 10, pp. 1164-1176 (June 1975).

Table 9-1

NEEDS FOR INFORMATION ON GENERAL HAZARDOUS WASTE RISKS AND BENEFITS

Need No. 1 Type of data: Maximum permissible tolerance
Chapters cited: 2 and 7

Inadequacy: Permissible tolerances (unless zero) should be based on observed threshold effects. Threshold effects have never been demonstrated for most hazardous wastes.

Research recommendations: Review permissible tolerance standards to find supportive evidence for threshold assumptions. If none, adopt a different type of standard for the waste in question.

Need No. 2 Type of data: Process flow and disposal
Chapter cited: 2

Inadequacy: System component definitions and evaluations are needed to assess system behavior.

Research recommendations: Initiate more careful work to process flows leading to waste products.

Need No. 3 Type of data: Contaminant dispersion
Chapter cited: 6

Inadequacy: Generalizable dispersion models suitable for risk analyses are not available.

Research recommendations: Develop dispersion models in all media for risk analysis purposes.

Need No. 4 Type of data: Inter-media contaminant transfers
Chapter cited: 6

Inadequacy: No generalizable model is available.

Research recommendations: Develop generalized inter-media transfer models for risk analysis purposes.

One other research opportunity was noted, not from the deficiencies of published research but from the potential applications of comprehensive trade-off models such as the one derived here. This opportunity involves the decision analysis concept of "expected value of perfect information." According to that concept, the value of obtaining perfect information by resolving all uncertainties (such as by eliminating all of the confidence limits in Figure 8-2) can be calculated from the probability distributions of the uncertainties and their relative influences on the final decision. The value of partial information that might correspond to a reduced confidence interval of one of the variables can be derived in the same manner.

These "value of information" analyses might be carried out to estimate the potential value of research to reduce risk and benefit uncertainties associated with a particular hazardous waste. Then this value of research can be compared to the anticipated benefits of initiating the optimal control alternative. The result (adjusted for the estimated time, money, and resolving power of the research) will be a first-order estimate of the relative advantage, given existing uncertainties, of initiating a control program versus conducting more study.

Cadmium and Asbestos Examples

The "value of information" methodology, as well as other techniques described in this chapter, can best be seen by application to our example waste cases. Since none of the examples have proved to be very promising as program alternatives, ranking and research applications may seem slightly unrealistic, but at least they can be related to actual data.

Cadmium

By referring to Figure 8-3, we can illustrate for one cadmium control alternative--the zinc smelter scrubber--how to carry out the selection and ranking procedures that were described above. In the selection step, we can see that "alternative X" (the smelter scrubber) does not meet the constraint representing any reasonable "human life valuation." However, if it did meet that constraint the next step would be to rank it with other acceptable alternatives by one of the rules shown in Figure 9-3.

For example, if the smelter scrubber were compared to the "status quo" alternative according to the "risk level" decision measure, it would be preferred under all decision principles except "regret" because it reduces the risk. ("Regret" attempts to minimize uncertainty, and since the status quo alternative has less uncertainty, it will always be preferred under the "regret" principle.) Conversely, "status quo" would win under all decision principles if they were compared according to "net benefit," because it doesn't cost anything.

The smelter scrubber alternative has a greater "mean lives saved" value, a smaller mean cost, and a larger uncertainty interval in both dimensions than the municipal incinerator alternative (not shown in Figure 8-3). It will therefore be preferred to the municipal incinerator program under all of the decision principles except "regret."

In examining the two cadmium alternatives, we encountered a number of specific research and information needs that are formulated in Table 9-2. Many of these needs can be met with quite small efforts, but until they are resolved they will cast large uncertainties over estimates of the values of cadmium control measures.

Asbestos

Asbestos studies have also left many unresolved questions, but our study has not pursued them in detail. Neither of the asbestos alternatives examined here seemed desirable under our decision rules because neither demonstrates any significant cadmium risk reduction. Therefore, we have not attempted to apply the selection and ranking procedures to

Table 9-2

NEEDS FOR INFORMATION ON CADMIUM
RISKS AND BENEFITS

Need No. 1 Type of Data: Standards
Chapter Title: [illegible]

Inadequacy: Standards for different media and environmental conditions are not systematically integrated.

Research Recommendations: [illegible] types of [illegible] consistent with one another.

Need No. 2 Type of Data: Emissions
Chapter Title: [illegible]

Inadequacy: Statistical data are insufficient for constructing a complete material balance analysis [illegible] from mining and refining and to water [illegible] are particularly deficient.

Research Recommendations: Conduct a comprehensive [illegible] material [illegible] in the environment.

Need No. 3 Type of Data: [illegible]
Chapter Title: [illegible]

Inadequacy: [illegible]

Research Recommendations: Obtain more reliable estimates of operating [illegible]

Need No. 4 Type of Data: [illegible]
Chapter Title: [illegible]

Inadequacy: [illegible]

Research Recommendations: [illegible]

Need No. 5 Type of Data: [illegible]
Chapter Title: [illegible]

Inadequacy: [illegible]

Research Recommendations: [illegible]

Need No. 6 Type of Data: [illegible]
Chapter Title: [illegible]

Inadequacy: [illegible]

Research Recommendations: [illegible]

Need No. 7 Type of Data: [illegible]
Chapter Title: [illegible]

Inadequacy: [illegible]

Research Recommendations: [illegible]

Need No. 8 Type of Data: [illegible]
Chapter Title: [illegible]

Inadequacy: [illegible]

Research Recommendations: [illegible]

them. However, the research and information needs outlined in Table 9-3 were derived from our studies of asbestos risk-benefit trade-offs. Like the earlier tables, this one summarizes a list of research tasks that could serve to resolve some of the most uncertain questions about hazardous waste risks, benefits, and their interrelationships for decision-making.

Table 9-3

NEEDS FOR INFORMATION ON ASBESTOS RISKS AND BENEFITS

Need No. 1 Type of data: Standards
Chapters cited: 2 and 7

Inadequacy: Asbestos standards are implicitly based on the threshold limit concept, yet there is little plausible evidence for the value or even the existence of such a threshold. Furthermore, the various standards seem too variable and too different in their measurement requirements.

Research recommendations: Develop an asbestos exposure model and reconcile it with the different concentration measurement methods. From the model, recommend more uniform and consistent standards.

Need No. 2 Type of data: Pollution
Chapter cited: 3, 4, and 6

Inadequacy: Evidence on sources of asbestos pollution is contradictory, and little is known of resuspension and recirculation patterns.

Research recommendations: Initiate a substantial study designed to discover the mechanisms and pathways of asbestos pollution.

Need No. 3 Type of data: Control costs
Chapter cited: 4

Inadequacy: Variations of control costs with size of plant are not known.

Research recommendations: Derive a cost sensitivity model for asbestos plant controls.

Need No. 4 Type of data: Dose-damage functions
Chapter cited: 7

Inadequacy: Major data sources imply differences of a factor of 5 on derived dose-damage functions.

Research recommendations: Reconcile existing data.

Need No. 5 Type of data: Cumulative dosages
Chapter cited: 7

Inadequacy: Cumulative asbestos dosage estimates are all based on reconstructed assumptions rather than observations, so their reliability is suspect.

Research recommendation: Initiate a controlled long-term experimental program to obtain reliable dosage data.

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Asb, Cd	ACGIH (1970) "Threshold Limit Values of Airborne Contaminants and Intended Changes Adopted by ACGIH for 1970," Amer. Conf. of Governmental Industrial Hygienists (1973).
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*	
gen	General
R/B	Risk/Benefit
Asb	Asbestos
Cd	Cadmium

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Topic

Cd ACHINGER (1970)

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